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LEFT-TURN SIGNAL WARRANT PROCEDURES: A SYNTHESIS OF PRACTICE

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LIST OF ACRONYMS

% LT Index	Percentage Left-Turn Index
ATSPM	Automated Traffic Signal Performance Measure
Caltrans	California Department of Transportation
CL	Capacity of a Lane
CBD	Central Business District
CMF	Crash Modification Factor
DOT	Department of Transportation
DSS	Decision Support System
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FYA	Flashing Yellow Arrow
G/C	Green Time Over Cycle Time
HCM	Highway Capacity Manual
HSM	Highway Safety Manual
INDOT	Indiana Department of Transportation
ITE	Institute of Transportation Engineers
LT	Left-Turn
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
OSR	Operational Safety Report
PDO	Property Damage Only
PLT	Protected-Only Left-Turn
PPLT	Protected/Permissive Left-Turn
RTC	Regional Transportation Commission
SSAM	Surrogate Safety Assessment Model
TAC	Technical Advisory Committee
TMC	Traffic Management Center
TRB	Transportation Research Board
UDOT	Utah Department of Transportation
UTRAC	Utah Transportation Research Advisory Council

v/c	Volume to Capacity
V_{LT}	Left-Turn Volumes
V_{OPP}	Opposing Through Volumes
vph	Vehicles per Hour
$vphpl$	Vehicles per Hour per Lane

EXECUTIVE SUMMARY

This research evaluated the current left-turn warranting procedures and guidelines for the Utah Department of Transportation (UDOT) by conducting a synthesis of practice regarding left-turn installation from state departments of transportation (DOTs) as well as city, county, and research organizations that may have such guidelines. The overall objective was to synthesize left-turn warranting procedures across the nation and to compare the information gathered with the UDOT warranting procedures and guidelines and to make limited recommendations on possible ways to improve the current process.

A background of UDOT's left-turn signal warrants was established that emphasizes the goals and tasks of this research. An analysis of the UDOT warranting procedures and guidelines including the volume-based warrant, history of severe left-turn crashes, and procedures dealing with cycle failure and queuing issues was conducted. A review of the University of Utah's research on left-turn policies by state was also completed. Next, a literature review was organized on recent research related to left-turn warrants.

As part of the research effort two surveys were conducted. The first survey that was completed gathered information from various state agencies across the United States about state policy regarding flashing yellow arrow (FYA) installations. Information related to the state's warrants and guidelines, time-of-day signal phasing, and state policy on re-evaluating signal phasing was gathered as a part of this effort. The second survey that was performed can be considered a supplement to the University of Utah survey that gathered information regarding left-turn signal phasing from non-responder states to the University of Utah survey as well as several other cities, counties, and transportation agencies throughout the United States.

After analyzing the survey responses and the findings from the literature review, limited recommendations regarding left-turn warrant policies were given. Recommendations for future research were provided including: an analysis of decision boundaries for left-turn treatments, several different methods for changing and/or re-evaluating the current volume criteria, time-of-day and FYA warrants, and a record of decision making.

1.0 INTRODUCTION

1.1 Background

The Utah Department of Transportation (UDOT) established guidelines for left-turn phases at signalized intersections on November 13, 2014. Research studies have been conducted since these guidelines were established including a review of the left-turn phasing criteria conducted by Hales Engineering in July 2016 (Hales Engineering, 2016) and research currently being conducted by the University of Utah on safety effects of protected/permissive left-turn phases (Shea et al., 2016). Each of these studies provides recommendations and information related to the warranting procedures and guidelines for the installation of left-turn phasing.

There is a need to further evaluate the guidelines and procedures provided for left-turn installation in the state so that the guidelines can be kept up to date with the most recent technological, operational, and safety advances. The additional evaluation should include the collection of additional warrant, data, guidelines, procedures, and time-of-day criteria for left-turn phasing; including protected left-turn phasing, permitted phasing, protected/permissive left-turn phasing, and discussion of flashing yellow arrow (FYA) installations.

1.2 Research Objectives

This research evaluates the current left-turn warranting procedures and guidelines for UDOT by conducting a synthesis of practice regarding left-turn phasing installation from state departments of transportation (DOTs) as well as city, county, and research organizations. The information gathered will be compared with the UDOT warranting procedures and guidelines to provide recommendations on ways to improve the current process. This is accomplished by:

- 1) Reviewing current UDOT warranting procedures and guidelines documentation, including any recent updates to the procedures.
- 2) Reviewing the University of Utah research on “Safety Effects of Protected and Protected/Permitted Left-Turn Phases” including a review of the state DOT survey

conducted as part of the research and identifying what additional information (if any) would be needed to meet the objectives of the study and request information accordingly.

- 3) Contacting other organizations including cities, counties, and research organizations to supplement the state DOT data gathered by the University of Utah research team to be used in the synthesis.
- 4) Comparing the information gathered in the synthesis with current left-turn warranting procedures and guidelines in Utah and recommending ways to improve the current warranting procedures and guidelines.

1.3 Benefits of the Project

UDOT will benefit from this research by understanding differences between national left-turn warranting procedures and guidelines as compared with UDOT's current left-turn warranting procedures and guidelines. The results of the research will help to identify possible changes and/or new recommendations on left-turn warrant procedures and guidelines to improve safety and operations on roadways across the state.

1.4 Organization

The body of the report and appendices are organized as follows: Chapter 1 includes the background, research objectives, and benefits of this left-turn warrant research. Chapter 2 includes a summary of the UDOT warranting procedures and guidelines including an analysis of the volume-based warrant, history of severe left-turn crashes, and cycle failure/queuing issues. Chapter 3 includes a summary of research conducted by a research team at the University of Utah Traffic Lab. The summary includes left-turn phasing policies by state, the safety effects of changing left-turn phasing, and a summary of information learned from the research team's literature review contained in the report. Chapter 4 includes a literature review of variable left-turn phasing by time of day, decision boundaries for left-turn treatments, and the operational and safety impacts of the use of FYA. Chapter 5 contains a synthesis of practice which includes two surveys conducted by the research team in an effort to understand the warranting procedures and guidelines pertaining to left-turn signal phasing and FYA for various states throughout the

country. Chapter 6 contains recommendations regarding future research and additional topics such as FYA and left-turn warrants. Chapter 7 includes the conclusion and summary of findings. Following the chapters are several appendices to provide supplemental data for the analyses.

2.0 UDOT WARRANTING PROCEDURES AND GUIDELINES REVIEW

2.1 Introduction

UDOT established their most recent guidelines for left-turn phases at signalized intersections on November 13, 2014. The guidelines are comprised of a flowchart of recommended criteria for use with warranting left-turn phasing at signalized intersections, shown in Figure 2-1 with more details provided in Appendix A. According to the guidelines a left-turn phase may be installed with left-turn volumes as low as 100 veh/hr where there is a history of severe left-turn crashes. Protected left-turn signal phasing installation is more likely to occur when there are volumes greater than 100 veh/hr, three or more opposing through lanes, and/or a posted speed limit of 60 mph or higher. The left-turn phase is recommended “after less restrictive measures to reduce delay, congestion, and crashes have been considered. The overall signalized corridor/network operations should be considered when evaluating the impacts of left-turn phasing. Even if the criteria in the flowchart are met for left-turn phasing, engineering judgment should be used to determine whether left-turn phasing is implemented” (UDOT, 2014).

According to the guidelines in Figure 2-1, the analyst must first choose between three options based on the left-turn volume of the intersection: below 100 veh/hr, between 100 and 250 veh/hr, or over 250 veh/hr. Each of these options leads to the next criteria of the flowchart guidelines, including yes/no questions about:

- History of severe left-turn crashes
- Cycle failure/queuing issues
- Four opposing through lanes
- Speed limit greater than or equal to 60 mph
- Results of a safety study that would determine if the intersection needs Protected Left-Turn Signal Phasing

- The volume-based warrant
- If dual left-turn lanes are warranted.

As the user follows the left-turn phasing guidelines flowchart s/he will need to answer the yes or no questions. The answers to the questions will lead the user to a recommendation of permissive left-turn phasing, permissive/protected left-turn phasing, or protected left-turn phasing.

The UDOT warranting procedures and guidelines, outlined in Figure 2-1, can be broken down into four main parts: 1) Volume-Based Warrant, 2) Dual Left-Turn Signal Warrants, 3) History of Severe Left-Turn Crashes, and 4) Cycle Failure/Queuing Issues. Each of these will be discussed in detail in this chapter.

2.2 Volume-Based Warrant

As shown in Figure 2-1, Volume-Based Warrants include volume cross product thresholds, where the cross product is defined as the left-turn volume multiplied by the opposing through volume. The current procedures and guidelines include volume cross product thresholds as outlined in Table 2-1.

Table 2-1 Current UDOT Volume Cross Product Thresholds (UDOT, 2014)

UDOT Left-Turn Phasing Criteria		
Number of Opposing Lanes	Volume Cross Product	
	Random Arrivals	Platoon Arrivals
1	50,000	60,000
2 or 3	100,000	120,000
Adopted November 13, 2014		

Left-Turn Phasing Guidelines

Updated November 13, 2014

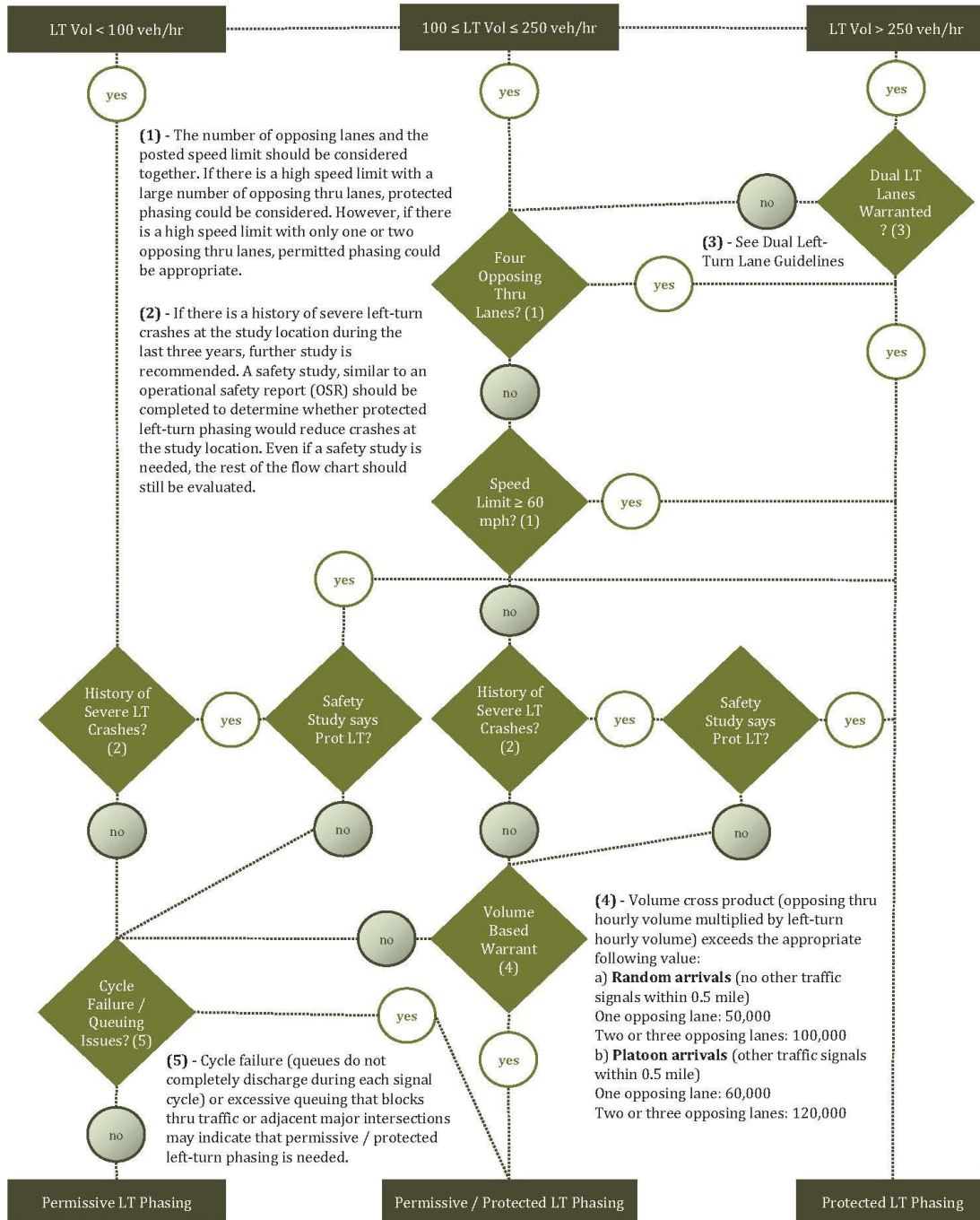


Figure 2-1 UDOT Left-Turn Phasing Guidelines (UDOT, 2014)

As can be seen in Table 2-1 there are different cross product thresholds for left-turn phasing based on the number of opposing lanes and the volume of traffic. It should be noted that currently, “opposing right-turning vehicles are excluded from the volumes on an approach when calculating the volume cross product for a left-turn movement. Observations by engineers in the field during data collection indicate that right-turning vehicles may conflict with the opposing left-turn movement as much as vehicles in the through lanes. Pedestrians can also conflict with the left-turn movement” (Hales Engineering, 2016). The inclusion of right-turning vehicles and pedestrians in the volume cross product thresholds will be discussed further in Chapter 6 of this report.

Hales Engineering provided the research team with a memorandum written to UDOT containing a comparison of the volume cross product threshold values with values recommended by other agencies, and a summary of an analysis completed by Hales Engineering to determine how to best include right-turning vehicles in the volume cross product calculations. The Hales Engineering memorandum provided comparisons of UDOT procedures with guidelines published by the Highway Capacity Manual (HCM) (TRB, 2010) and the Federal Highway Administration (FHWA). Table 2-2 summarizes the cross-product threshold outlined in the HCM, while Table 2-3 summarizes the FHWA guidelines.

Table 2-2 HCM Volume Cross Product Thresholds (TRB, 2010)

HCM Left-Turn Phasing Criteria	
Number of Opposing Lanes	Volume Cross Product
1	50,000
2	90,000
3	100,000

Table 2-3 FHWA Volume Cross Product Thresholds (Rodegerdts et al., 2004)

FHWA Left-Turn Phasing Criteria		
Number of Opposing Lanes	Volume Cross Product	
	Random Arrivals	Platoon Arrivals
1	45,000	50,000
2	90,000	100,000
3	Install Left-Turn Phasing	

The traffic volumes for one and three opposing lanes in the HCM are the same as the volume cross product for random arrivals for UDOT's left-turn phasing criteria. The major difference is that the HCM provides an additional recommendation based on having two opposing lanes while UDOT combines two and three opposing lanes into the same volume criteria. Another major difference between these two volume cross product thresholds is that UDOT uses separate criteria for random and platoon arrivals. According to the UDOT guidelines in Figure 2-1, random arrivals are defined as arrivals with "no other traffic signals within 0.5 miles upstream" and platoon arrivals are arrivals with "other traffic signals within 0.5 miles upstream" (UDOT, 2014). As can be seen in Table 2-1 the volumes increase when the arrivals are defined as platoon arrivals.

As can be seen in Table 2-3, UDOT has a similar structure to the FHWA volume cross product; however, the volumes that UDOT uses are more consistent with the HCM than the FHWA guidelines. Additionally, the FHWA recommends that left-turn phasing be installed if there are three or more opposing lanes, regardless of the cross product. In contrast, both UDOT and the HCM assign volume thresholds to three opposing lanes meaning that if there are three opposing through lanes it doesn't automatically receive a more protected signal phasing.

With respect to the volume-based warrant section of UDOT's left-turn signal warrants, UDOT has adopted a hybrid of the FHWA and HCM volume cross product thresholds. UDOT has adopted the system of having two different warrants depending on the type of arrival from the FHWA. From the HCM the actual volumes used in the cross product have been adopted.

2.3 Dual Left-Turn Signal Warrants

In addition to the left-turn warrants that have already been discussed, UDOT has outlined specific requirements for dual left-turn lanes. The first requirement when considering dual left-turn lanes is that a capacity sensitivity analysis should be performed using Synchro software with the following default analysis values (UDOT, 2014):

- 1) Cycle length: 120 seconds
- 2) Ideal saturation flow rate: 1900 vehicles per hour per lane (vphpl)
- 3) Percent heavy vehicles: 2%
- 4) Lane widths: 12 feet
- 5) Analyze with no parking and non-central business district (CBD)
- 6) Optimize splits

After the Synchro model has been performed, the analyst consults the guidelines for the recommended left-turn volumes and the opposing through volume to capacity (v/c) ratio summarized in Table 2-4. The UDOT guidelines note that the table is to be used in assisting to make the decision for dual left-turns and that the v/c ratio is calculated using HCM 2010 methodologies (UDOT, 2014).

Table 2-4 UDOT Dual Left-Turn Lane Capacity Analysis Guidelines (UDOT, 2014)

Left-Turn Volume (veh/hr)	Opposing Through \geq	Recommend
250-269	0.95	Dual Left-Turn Lanes
270-279	0.75	Dual Left-Turn Lanes
280-319	0.65	Dual Left-Turn Lanes
320-359	0.6	Dual Left-Turn Lanes
360-389	0.55	Dual Left-Turn Lanes
390-420	0.5	Dual Left-Turn Lanes
≥ 420		Dual Left-Turn Lanes

As can be seen in Table 2-4, there is an inverse relationship between the left-turn volume and the minimum required opposing through volume v/c ratios. As the left-turn volume increases the minimum required opposing v/c ratio decreases. In addition to the volume cross products outlined in Table 2-4 six other requirements or suggestions are provided as follows (UDOT, 2014):

- 1) The number of hours where left-turn volume meets the guidelines in the capacity analysis in Table 2-4 should be considered where the dual left-turn lanes provide a benefit. A comparison with the vehicle delays should be made during the other nonpeak hours in the day.
- 2) The location of the intersection where the dual left-turn lanes are being considered should also consider the lane distribution that will be obtained. For example, if the intersection is close to a freeway on-ramp, there may not be good lane utilization since vehicles will favor the lane providing the best access to the ramp.
- 3) Consideration should be given for the need to minimize the green time given to left turns on one approach so that added green time is available for the other phases.
- 4) Compatibility of the dual left-turn lanes exclusive phasing operations with the signal coordination should be evaluated.
- 5) The Designer and Project Manager shall consult with the Region Traffic Operations Engineer and the Division of Traffic & Safety before adding dual left-turn lanes when the left-turn volume is less than 420 vehicles per hour (vph).
- 6) If there is no opposing through movement, such as at a three-way “T” intersection, then no additional signal phase is needed. Instead of using the above volume and v/c criteria, consideration should be given to opposing pedestrian phases, available right-of-way needed for the additional lane, and existing left-turn queue lengths at the intersection. If cycle failure (queue doesn’t clear during each signal cycle) is occurring often, dual left-turn lanes should be considered.

2.4 History of Severe Left-Turn Crashes

As noted previously, one of the considerations for a left-turn warrant is an analysis of severe crash history. The Highway Safety Manual (HSM) defines a crash as “a set of events that result in injury or property damage due to the collision of at least one motorized vehicle and may involve collision with another motorized vehicle, bicyclist, pedestrian, or object. Crash frequency is defined as the number of crashes occurring at a particular site, facility, or network in a one-year period” (AASHTO, 2010). Crash severity has been defined in the HSM according to the FHWA KABCO scale. The KABCO scale separates different crashes into various categories based on how severe the crashes are. The different categories are outlined as follows (AASHTO, 2010):

- K – Fatal injury
- A – Incapacitating injury
- B – Non-incapacitating injury
- C – Possible injury
- O – No injury/Property Damage Only (PDO)

Associated with each one of these categories is an assigned severity level and dollar amount that can be used in the analysis of crashes. According to UDOT research by Saito et al. (2016) these dollar amounts can be used in cost benefit analyses for projects. After the change in crashes has been estimated for a project, the benefits from preventing the crashes need to be converted into a monetary value. The first step in converting the benefits to a monetary value is to calculate the annual monetary value of crashes by severity to determine how the reduction in each crash severity level has created a benefit. There are several differing opinions on how these values of the different crash types should be calculated. The FHWA has completed research that establishes a basis for quantifying, in monetary terms, the human capital crash costs to society of fatalities and injuries from highway crashes. These estimates include the monetary losses to society associated with medical care, emergency services, property damage, lost productivity,

etc. (Saito et al., 2016). The FHWA values (as of 2010) that have been given for each crash severity level in the HSM are shown in Table 2-5 (AASHTO, 2010). These values have increased since that time.

Other state and local jurisdictions have adopted their own societal crash costs by crash severity and collision type, similar to Table 2-5. UDOT has its own set values associated with determining the value of each crash severity level. UDOT uses five crash severity levels that are presented on a KABCO scale. The major difference between the FHWA values and the UDOT values is that UDOT equalizes the scale for the fatal and disabling injuries so that the fatal crashes and the disabling injury crashes have the same monetary value. These values can be seen in Table 2-6. This has been done to balance the benefit of reducing fatal and serious injury crashes since the circumstances of each are often very similar. Disabling injuries may cost more over time than fatal crashes because of lingering medical costs and the persons involved in these incapacitating injuries being prevented from ever working again (Saito et al., 2016).

**Table 2-5 Benefit Value per Crash Provided by the FHWA for Each Crash Type
(AASHTO, 2010)**

Severity Description	KABCO Severity	UDOT Severity No.	Value
PDO	O	1	\$7,400.00
Possible Injury	C	2	\$44,900.00
Evident Injury	B	3	\$79,000.00
Disabling Injury	A	4	\$216,000.00
Fatal	K	5	\$4,008,900.00

Table 2-6 Benefit Value per Crash Provided by UDOT for Each Crash Type (Saito et al., 2016)

Severity Description	KABCO Severity	UDOT Severity No.	Value
PDO	O	1	\$3,200.00
Possible Injury	C	2	\$62,500.00
Evident Injury	B	3	\$122,400.00
Disabling Injury	A	4	\$1,961,100.00
Fatal	K	5	\$1,961,100.00

In a meeting with Mr. Jeremy Searle from Hales Engineering it was explained that when an analysis of an intersection is being completed and there are any severe crashes within the past three years associated with the left turn, a more thorough investigation must be completed. This is included in Figure 2-1 where the flowchart states that “If there is a history of severe left-turn crashes at the study location during the last three years, further study is recommended. A safety study, similar to an operational safety report (OSR), should be completed to determine whether protected left-turn phasing would reduce crashes at the study location. Even if a safety study is needed, the rest of the flowchart should still be evaluated” (UDOT, 2014). In the past UDOT had a set number of crashes per unit of time that would warrant using a more restrictive left-turn phase. This was changed to encourage a more detailed crash analysis. New tools that have been developed by UDOT have provided more crash information so that crashes can be evaluated more closely to determine if left-turn phasing would have provided a safety benefit to the crashes at the study location. This allowed for the UDOT policy to become a set of guidelines, rather than a set number of crashes (Searle, 2017).

2.5 Cycle Failure/Queuing Issues

The fourth of four main parts of left-turn signal warrant analysis is that of cycle failure or queuing issues. As noted in the UDOT guidelines shown in Figure 2-1, cycle failure and queuing issues should be considered when conducting an analysis to ascertain if a left-turn signal should be used. Cycle failure is defined in Figure 2-1 as “queues that do not completely discharge during each signal cycle” (UDOT, 2014). The flowchart also makes note that queuing issues include “excessive queuing that blocks through traffic or adjacent major intersections that may indicate that permissive/protected left-turn phasing is needed” (UDOT, 2014). The cycle failure/queuing issues step of the flowchart can be seen in the bottom left hand corner of the flowchart. This step of the process is the last determining factor between the options of permissive left-turn phasing and protected/permissive left-turn phasing. If the intersection in question fails the criteria, meaning that there is a cycle failure or queuing issue after attempts are made in adjusting signal timing, then protected/permissive left-turn phasing is recommended for the intersection (Searle, 2017).

In the meeting with Mr. Searle, it was explained that this part of the UDOT guidelines is completed by quantifying the number or percent of cycle that a queue did not completely clear the intersection. If there are a minimal number of times that queuing or cycle failure occurs, permissive left-turn phasing may be assigned. If there is a significant number or percent of queuing or cycle failure, a protected/permissive left-turn phasing will be installed in order to reduce queuing and cycle failure. Since there are no specific guidelines for what is considered “minimal” or “significant” cycle failure/queuing issues, this area is largely left to engineering judgment (Searle, 2017).

2.6 Chapter Summary

Each one of the four main components of the UDOT 2014 updated guidelines for left-turn phasing at signalized intersections is an important part of the warranting process. The volume-based warrant establishes the minimum volumes that are recommended for each of the three different left-turn signal phases. The dual left-turn signal warrants provide justification for dual left-turns as a function of left-turn volumes and v/c ratios. This history of severe left-turn crashes allows for a safer signal phase to be chosen if there is a history of severe crashes. Instead of a permissive left-turn phasing, protected/permissive left-turn phasing or protected left-turn phasing may be chosen if there is a safety concern that would be identified while researching the history of crashes at the intersection. The cycle failure/queuing issues component of the guidelines is the functionality component that helps the operational side of the traffic design. The intersection should be able to discharge the left-turn queue. If the intersection in question fails the criteria, meaning that cycle failure or queuing occur frequently, then protected/permissive left-turn phasing may be recommended for the intersection in order to help clear the queue during undersaturated traffic conditions.

3.0 University of Utah Research Review

3.1 Introduction

The University of Utah has been engaged in research that included an outreach effort to collect information on safety effects of protected and permitted left-turn phases from state DOTs that resulted in identifying left-turn phasing policies by state along with the associated safety information. Included in this chapter is a summary of left-turn phasing policies by state, the safety effects of changing left-turn phasing, and the University of Utah FYA literature review. The summary of left-turn phasing policies by state includes different methodologies for selecting left-turn phasing. Methodologies included in this chapter include guidelines set forth by the Institute of Transportation Engineers (ITE), FHWA, state adapted versions of ITE and FHWA guidelines, and formula-based approaches.

3.2 Left-Turn Phasing Policies by State

As of June 2017, the University of Utah has an ongoing research project focused on the *Safety Effects of Protected and Protected/Permissive Left-Turn Phases*. As a part of this research, an outreach effort was conducted to collect information on the state of practice for left-turn phasing from all 50 states. The survey resulted in 44 responses from state DOTs. Based on the results of the research, each of the states were sorted into categories based on the type of left-turn phasing criteria reported. As shown in Table 3-1, DOTs were grouped by the type of criteria used to inform decisions on left-turn phases: ITE/FHWA Flowchart (8 states), FHWA guidelines (4 States), State-adapted criteria from ITE and FHWA guidelines (14 states), a formulaic set of criteria (6 states), and no statewide guidelines (12 states). Each of these will be discussed in the following subsections.

Table 3-1 Left-Turn Phasing Policies by State (Shea et al., 2016)

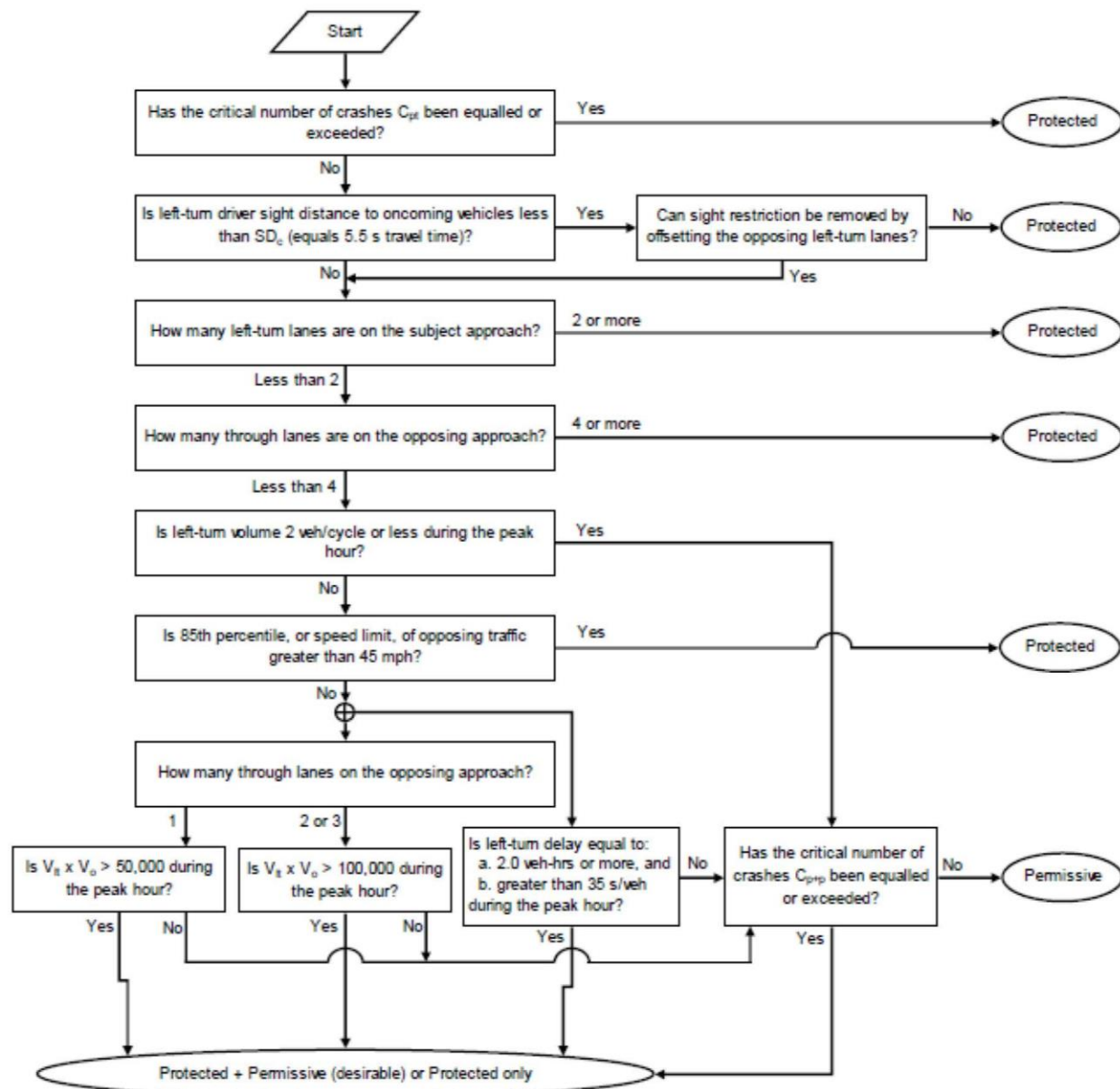
ITE/FHWA Flowchart (8 States)	FHWA Guidelines (4 States)	State Adapted Criteria (14 States)	Formula-Based Approach (6 States)	No Statewide Guidelines (12 States)
Alaska Delaware Louisiana North Dakota Rhode Island South Dakota Texas Wyoming	Hawaii Kentucky Nevada Vermont	Arizona Georgia Michigan Minnesota Mississippi Nebraska New York North Carolina Oregon Pennsylvania South Carolina Tennessee Utah Wisconsin	Alabama Idaho Illinois Indiana Missouri Montana	Arkansas Connecticut Florida Iowa Kansas Maine Massachusetts New Hampshire Ohio Oklahoma Virginia Washington

*Non-Responding States: California, Colorado, Maryland, New Jersey, New Mexico, West Virginia

3.2.1 ITE/FHWA Flowchart

The FHWA Signal Timing Manual provides a flowchart created by ITE that incorporates several important decision-making criteria including crash history, sight distance, intersection geometry, left-turn volume, 85th percentile speed, through lane and left-turn cross product, and vehicle delay. The flowchart, shown in Figure 3-1, is meant to assist users in determining permissive, protected/permissive, or protected left-turn-only phasing by considering successive warranting criteria.

As shown in Figure 3-1, protected left turns are the first warrant outlined. While it is the first warrant outlined, it is based on worst-case scenarios including crashes and driver sight distance. As the user continues down the criteria, protected/permissive left-turn warrants are next, followed by permissive only.



Number of Left-turn Movements on Subject Road	Period During Which Crashes are Considered (years)	Critical Left-Turn-Related Crash Count When Considering Protected-only, C_{pt} (crashes/period)	When Considering Prot.+Perm., C_{ptp} (crashes/period)
One	1	6	4
One	2	11	6
One	3	14	7
Both	1	11	6
Both	2	18	9
Both	3	26	13

Oncoming Traffic Speed Limit (mph)	Minimum Sight Distance to Oncoming Vehicles, SD_c (ft)
25	200
30	240
35	280
40	320
45	360
50	400
55	440
60	480

Variables

V_{lt} = left-turn volume on the subject approach, veh/h

V_o = through plus right-turn volume on the approach opposing the subject left-turn movement, veh/h

Figure 3-1 Flowchart for Left-Turn Phasing Guidelines (FHWA, 2008)

According to Figure 3-1, safety warrants are first considered for left-turn phasing with the first based on crash history. The crash history warrant considers either one or both approaches for the subject road with corresponding 1, 2, and 3 year left-turn related crashes. Intersections with multiple left-turn-related crashes will warrant a protected left turn (refer to Figure 3-1 for specific values). The second safety decision is based on sight distance of the left-turn lane. Based on the guidelines, sight distance problems that cannot be addressed by offsetting the opposing left turns will warrant a protected left turn. The third safety decision is based on the number of left-turning or opposing through lanes, where the existence of two or more left-turn lanes or four opposing lanes will warrant a protected left turn. The fourth safety consideration is if the 85th percentile speed, or the speed limit, of the opposing vehicles to the left-turning movement is greater than 45 mph, the intersection will warrant a protected left turn. If safety considerations do not warrant a protected left turn, the next set of warrant considerations is for various traffic volume scenarios (FHWA, 2008).

Volume warrants consider both left-turn volumes (V_{LT}) and opposing through volumes (V_{OPP}). The first volume warrant criterion is part of the crash history considerations, where multiple left-turn-related crashes combined with two or more left-turning vehicles per cycle in the peak hour to warrant a protected/permmissive left turn. The second volume warranting criterion uses the cross product of the left-turning vehicles with the opposing through vehicles in conjunction with the number of opposing through lanes. When more opposing through lanes are present, a higher warranting cross product value is required to warrant protected/permmissive or protected-only signal phasing. The minimum cross product values for one, two, or three opposing through lanes are 50,000, 100,000, and 100,000, respectively. Each of the volume criteria will warrant a protected/permmissive left turn (desired) or protected left turn, leaving discretion to the traffic engineer or analyst conducting the study. If the volume warrant criteria do not warrant a protected/permmissive left turn or a protected left turn, the final warrant to be considered is vehicle delay (FHWA, 2008).

Vehicle delay considers both individual left-turn vehicle delay and the total left-turn vehicle hours of delay during the peak hour. According to the guidelines a 35 sec/veh delay or a 2.0 veh-hr delay will warrant a protected/permmissive left turn (desired) or a protected left turn. In

the event that none of the earlier warranting criteria have been met, the default phasing is permissive only (FHWA, 2008).

3.2.2 FHWA Guidelines

The report completed by Shea et al. (2016) notes that there are four states that utilize the FHWA informational guide, *Signalized Intersections: An Informational Guide (2nd Edition)* (FHWA, 2013), that was published by the FHWA Safety Program Office. The state adapted version of these guidelines will be discussed in this section. The difference between the FHWA guidelines and the ITE/FHWA flowchart is that the FHWA guidelines provide a separate protected left-turn-only volume cross product beyond the protected/permissive left-turn warrants. The ITE/FHWA flowchart recommends either protected/permissive left-turn or protected left-turn only, but does not recommend protected left-turn warrant criteria using the volume cross product of V_{LT} and V_{OPP} . The FHWA guidelines recommend protected left-turn criteria using the volume cross product as well as other criteria related to conditions common to urban (versus rural) settings and crash history.

According to the FHWA guidelines left-turn phasing (protected/permissive, permissive-protected, or protected only) should be considered if one or more of the following criteria are satisfied (FHWA, 2013):

- 1) A minimum of two left-turning vehicles per cycle and the product of opposing and left-turn hourly volumes exceeds the appropriate following value:
 - a) Random arrivals (no other traffic signals within 0.5 mi):
One opposing lane: 45,000; Two opposing lanes: 90,000
 - b) Platoon arrivals (other traffic signals within 0.5 mi):
One opposing lane: 50,000; Two opposing lanes: 100,000
- 2) The left-turning movement crosses three or more lanes of opposing through traffic.
- 3) The posted speed of opposing traffic exceeds 45 mph.

- 4) Recent crash history for a 12-month period indicates five or more left-turn collisions that could be prevented by the installation of left-turn signals.
- 5) Sight distances to oncoming traffic are less than minimum distances.
- 6) The intersection has unusual geometric configurations, such as five legs, when an analysis indicates that left turn or other special traffic signal phases would be appropriate to provide positive direction to the motorist.
- 7) An opposing left-turn approach has a left-turn signal or meets one or more of the criteria in this list.
- 8) An engineering study indicates a need for left-turn signals. Items that may be considered include, but are not necessarily limited to, pedestrian volumes, traffic signal progression, freeway interchange design, maneuverability of particular classes of vehicles, and operational requirements unique to preemption systems.

According to the FHWA guidelines, the type of phasing to use is based on the following criteria (FHWA, 2013):

- 1) Insignificant number of adequate gaps in opposing traffic to complete a left turn.
- 2) Permissive left-turn phasing may be considered at sites that do not satisfy any of the left-turn phasing criteria listed above.
- 3) Protected/permissive left-turn phasing may be considered at sites that satisfy one or more of the left-turn phasing criteria listed in the first list but do not satisfy the phasing criteria for protected-only phasing (see criterion 5 below). Protected-permissive phasing is not appropriate when left-turn phasing is installed as a result of an accident problem.
- 4) Permissive-protected left-turn phasing may be considered at sites that satisfy the criteria for protected-permissive phasing and one of the following criteria:

- a) The movement has no opposing left turn (such as at a T-intersection) or the movement is prohibited (such as at a freeway ramp terminal).
 - b) A protected-permissive signal display is used that provides the left-turning vehicle with an indication of when the driver must yield to opposing traffic, a FYA, or other such devices.
- 5) Protected-only left-turn phasing should be considered if any one of the following criteria is satisfied:
- a) A minimum of two left-turning vehicles per cycle and the product of opposing and left-turn hourly volumes exceed 130,000-150,000 for one opposing lane or 300,000 for two opposing lanes.
 - b) The posted speed of opposing traffic exceeds 45 mph.
 - c) Left-turning crashes per approach (including crashes involving pedestrians) equal four or more per year, or six or more in two years, or eight or more in three years.
 - d) The left-turning movement crosses three or more lanes of opposing through traffic.
 - e) Multiple left-turn lanes are provided.
 - f) Sight distances to oncoming traffic are less than required minimum distances.
 - g) The signal is located in a traffic signal system that may require the use of lead-lag left-turn phasing. This criterion does not apply if:
 - i) An analysis indicates lead-lag phasing is not needed.
 - ii) An analysis indicates that protected-permissive phasing reduces total delay more than lead-lag phasing.

- h) A protected-permissive signal display is used that allows a permissive left turn to operate safely opposite a lagging protected left-turn phase (See Chapter 2 of (FHWA, 2013) for discussion of left-turn trap).
- i) An engineering study indicates a need for left-turn signals. Items that may be considered include, but are not necessarily limited to, pedestrian volumes, traffic signal progression, freeway interchange design, maneuverability of particular classes of vehicles, number of older drivers, and operational requirements unique to preemption systems.

3.2.3 State-Adapted Criteria

There were a total of 14 states that had instituted their own state-adapted criteria. These adaptations included modifying, removing, and adding warrant criteria to already existing methods such as the ITE/FHWA flowchart. Table 3-2 contains information regarding state-adapted criteria for left-turn warrants including a summary of the modifications to the left-turn flowcharts and informational guides. Most of the modifications are changes to the cross-product values that result in an increase in the volume criteria for protected left-turn only and a decrease in the volume criteria for protected/permissive left-turn phasing (Shea et al., 2016). In Table 3-2 protected/permissive left turn (PPLT) and protected-only left-turn (PLT) phasing are referred to by their acronyms. Left turn (LT) is denoted by its acronym as well.

Table 3-2 Cross Product and Crash History for State-Adapted Criteria (Shea et al., 2016)

State	Cross Product	Crash History
Arizona	PPLT: Rural: >50,000 (1 opposing lane) >100,000 (2 opposing lane) >150,000 (3 opposing lane) Urban: >75,000 (1 opposing lane) >150,000 (2 opposing lane) >225,000 (3 opposing lane) PLT with 3 opposing lanes	One lane approach: 4 per year; 6 per 2 years. Two lane approaches: 6 per year; 10 per 2 years.

Note: Protected/permissive left turn (PPLT), protected-only left turn (PLT), and left turn (LT)

Table 3-2 Continued

State	Cross Product	Crash History
Georgia	PPLT: >50,000 (1 opposing lane) >100,000 (2 opposing lanes) PLT with 3 opposing lanes	4 per year or 6 per 2 years.
Michigan	PPLT: >50,000 (1 opposing lane) >100,000 (2 opposing lanes) Any volume (3 opposing lanes)	If crash pattern would be corrected
Minnesota	PPLT: >50,000 (1 opposing lane) >100,000 (2 opposing lanes) PLT: >80,000 (1 opposing lane) >100,000 (2 opposing lanes) Any volume (3 opposing lanes)	5 per 3 years.
Mississippi	PPLT: Urban >40,000 (1 opposing lane) >60,000 (2 opposing lanes) Rural >30,000 (1 opposing lane) >40,000 (2 opposing lane) PLT: >150,000 (1 opposing lane) >60,000 (2 opposing lanes)	Urban: 4 per year per approach; Rural: 3 per year per approach.
New York	>50,000 (1 opposing lane) >100,000 (2 opposing lanes) With left-turn volume >50 in peak hour	5 or more crashes year.
Ohio	PPLT: >100,000 (1 or 2 opposing lanes) PLT with 3 opposing lanes (not mandatory)	5 LT crashes per year.
Oregon	PPLT: >50,000 (1 opposing lane) >100,000 (2 opposing lanes) PLT: >150,000 (1 opposing lane) >300,000 (2 opposing lanes) Any volume (3 opposing lanes)	5 LT crashes per year.

Note: Protected/permissive left turn (PPLT), protected-only left turn (PLT), and left turn (LT)

Table 3-2 Continued

State	Cross Product	Crash History
Pennsylvania	(1 opposing lane) PPLT without LT lane: >45,000 for 2 peak hours (2 opposing lanes) PPLT with LT lane: >50,000 for 2 peak hours (1 opposing lane) >65,000 for 2 peak hours (2 opposing lanes) PLT >67,5000 for 2 peak hours (1 opposing lane) >90,000 for 2 peak hours (2 opposing lanes)	
Rhode Island	PPLT: >50,000 (1 opposing lane) >100,000 (2 or 3 opposing lanes) PLT only (4 opposing lanes)	One approach lane: 4 per year; 6 per 2 years; 7 per 3 years. Two approach lanes: 6 per year; 9 per 2 years; 13 per 3 years.
South Carolina	PPLT: >100,000 PLT only (3 opposing lanes)	5 LT crashes per year.
Tennessee	>50,000 (1 opposing lane) >90,000 (2 opposing lanes) >110,000 (3 opposing lanes)	One approach: 4 per year; 6 per 2 years. Two approaches: 6 per year; 10 per 2 years.
Utah	PPLT: Random arrival: >50,000 (1 opposing lane) >100,000 (2 or 3 opposing lanes) Platooned arrival: >60,000 (1 opposing lane) >120,000 (2 or 3 opposing lanes) PLT: High Speeds & 3 opposing lanes	History of severe crashes in past 3 years

Note: Protected/permissive left turn (PPLT), protected-only left turn (PLT), and left turn (LT)

Table 3-2 Continued

State	Cross Product	Crash History
Vermont	PPLT: Random arrival: >45,000 (1 opposing lane) >90,000 (2 opposing lanes) Platooned arrival: >50,000 (1 opposing lane) >100,000 (2 or 3 opposing lanes) PLT: >130,000 (1 opposing lane) >300,000 (2 opposing lanes) Any volume (3 opposing lanes)	5 per year.

Note: Protected/permissive left turn (PPLT), protected-only left turn (PLT), and left turn (LT)

The state of Utah is among the list of states that have their own state-adapted criteria. Some states such as Arizona and Mississippi have enhanced their volume cross product values to be divided into several different categories and to allow for several different scenarios. Arizona and Mississippi both have different criteria for rural and urban intersections. Each is then subdivided into criteria based on the number of opposing lanes that exist at the intersection in question. Only two of the states that have their own state-adapted criteria, Utah and Vermont, have specified different volume cross product values based on the method of arrival, random or platoon. As shown in Table 3-2, both the random and platooned arrival volume cross product threshold values for Utah are higher than those in Vermont. The other difference between the two states is that Vermont has specific volume criteria for protected left-turn phasing.

Not all states listed in Table 3-2 have a specific crash history criterion. Several states including Arizona, Kansas, Rhode Island, and Tennessee have their crash history criterion subdivided by the number of approaches. For example, Arizona has a crash history criterion subdivided into one and two approaches. From there the state has two criteria within each of those approach criterion. For one approach, there is the crash history criterion of four crashes per year or six crashes every two years. The state of Mississippi has the crash history criterion subdivided into urban and rural criteria. For rural criterion three crashes per year per approach meet the warrant for left-turn signal phase while in urban settings four crashes per year per approach warrant. This would allow for rural areas to install a left-turn signal phase more easily than urban areas.

3.2.4 Formula-Based Approach

There were a total of six states that do not use set warranting values and opt to use a formula based approach. These formulas and methods of evaluation are shown in Table 3-3. For each of the six states listed, capacity and safety are both taken into consideration, but only Alabama and Idaho have a set value for the crash history warrant.

Table 3-3 Formula-Based Criteria for Left-Turn Phase Consideration (Shea et al., 2016)

State	Variables and Criteria
Alabama	Critical left-turn volume based on opposing through lane number and volume adjusted for effective green time over cycle time (G/C); 5 LT crashes per year.
Idaho	Critical left-turn volume based on opposing through lane number and volume adjusted for G/C; 5 LT crashes per year.
Illinois	Consider left-turn phase where the demand for left turning exceeds the left-turn capacity of the approach lane; consider crash history but not set guidelines
Indiana	Capacity of a lane (CL) where demand exceeds capacity of approach lane; $CL = 1200G - V_{OPP}$. G = % green time; consider crash history but no set guidelines.
Missouri	When LT + opposing volume exceeds $600 * G/C$; 5 LT crashes per year on same approach; vehicle conflicts exceed 29 in an 11-hour day.
Montana	When LT volume exceeds LT capacity of approach lane, calculated as $(1,200 * G/C - Opposing Volume)$, not less than 2 veh/cycle; consider crash history but no set guidelines

3.2.5 No Statewide Guidelines

There were 11 states in the University of Utah survey that had not adopted guidelines or other techniques to warrant left-turn phasing. According to the University of Utah literature review and current state of practice these states that “rely on engineering analysis will use some form of data collection and analysis, but the final decision is up to the engineer and agency. Connecticut and Washington, for example, use traffic modeling software to perform a capacity analysis for each signal-phasing decision” (Shea et al., 2016). According to this same review, engineering judgment is referenced by all states, no matter the left-turn phasing method

employed. States perform an engineering study for each intersection and will defer to engineering judgment even when meeting some of the warrants while left-turn phasing is implemented in anticipation of future need in some cases. FYA includes the capability of accommodating permissive, protected/permissive, and protected only left-turn phasing depending on the time of day. Many states are in the trial phase for implementing FYA and continue to adjust signal phasing as crash history, operational data, and public feedback become available (Shea et al., 2016).

3.3 Safety Effects of Changing Left-Turn Phasing

The primary focus of the University of Utah research was to evaluate the safety effects of changes related to protected left turn and protected/permissive left-turn phasing. The focus of this portion of the University of Utah study was to summarize “what is currently known in the literature about the safety performance of alternative left-turn phasing options as one of the key elements involved in the decision process along with geometry, traffic turning volumes, and other operational-related considerations” (Shea et al., 2016). This included information regarding crash modification factors (CMFs), where CMFs are a measure of the safety effectiveness of a particular treatment or design element. A CMF is a multiplicative factor used to compute the expected number of crashes after implementing a specific countermeasure at a study site (Scurry, 2014). Table 3-4 summarizes the University of Utah findings by comparing the effects of changing from permissive left-turn phasing to protected/permissive or protected only left-turn phasing.

All of the studies addressed the effect of converting left-turn phasing from permissive to protected/permissive. Half of the studies also addressed the effect of converting left-turn phasing from permissive to protected-only. Out of the 14 crash type scenarios presented in the permissive to protected/permissive left-turn signal phasing category, five produced an insignificant change in crashes, five resulted in significant increases, and only four of the results in this category showed a significant decrease in crashes. Overall this would mean that the state DOT should require a safety impact study to be conducted due to the mixed results, and a traffic study should be conducted prior to any signal phasing changes at an intersection to analyze the potential safety effects of that change. According to the data shown in the permissive to

protected/permmissive left-turn conversions in Table 3-4, of the cases that had a significant increase in crashes per year, three of the five pertained to left-turn-only crashes, while the other two applied to all crashes.

The right columns of Table 3-4 contain information regarding permmissive to protected left-turn signal phasing. This category only contains seven different cases in comparison to the 14 cases that were on the permmissive to protected/permmissive left-turn side of the table. Of the seven cases that were examined, two of the cases did not produce significant results, of which both applied to cases that analyzed all crash types. The five remaining cases summarized in the table resulted in a significant decrease in crashes. More studies would need to be analyzed in order to provide a more conclusive evaluation, but based on the data that are provided in Table 3-4, it would seem that changing permmissive signal phasing to protected left turn is safer than changing permmissive phasing to protected/permmissive left turn.

3.4 University of Utah FYA Literature Review

As part of the University of Utah (Shea et al. 2016) research, a literature review was conducted to evaluate FYA installations and how signal phasing changes affect crash frequency. The study summarizes lessons learned in three different tables that analyze the effects of changing the left-turn phase from permmissive, protected/permmissive, and protected left-turn phases to FYA phases. These summary tables are shown in Table 3-5, Table 3-6, and Table 3-7. It should be noted that when discussing protected/permmissive left-turn signal phasing the signal head is a 5-section doghouse cluster in these tables. According to the review, approval and support for the FYA installation have allowed state and local agencies to implement flexible left-turn phasing operations. The 2009 Manual on Uniform Traffic Control Devices (MUTCD) includes the standard for FYA devices based on the National Cooperative Highway Research Program (NCHRP) Report 493, which states that, "...a flashing yellow arrow protected/permmissive left-turn display was consistently found to be equal or superior to existing protected/permmissive left-turn displays both in a laboratory environment and in cities where the display was experimentally implemented in the field" (Brehmer et al., 2003).

Table 3-4 Effects of Changing a Permissive Left-Turn Phase to a Protected/Permissive Left Turn or a Protected Left Turn Only (Shea et al., 2016)

Study	Treatment					
	Permissive to PPLT			Permissive to PLT		
	Sites	Crash Type	Effect	Sites	Crash Type	Effect
Harkey et al. (2008)	3	All Crashes	Not Significant	8	All Crashes	Not Significant
		Left-Turn Only	Not Significant		Left-Turn Only	Significant Decrease (CMF = 0.02)
Yu et al. (2009)	5	Left-Turn Only	Significant increase (CMF = 1.32)			
Srinivasan et al. (2012)	50 *	All Crashes	Significant increase (CMF = 1.08)			
		Left-Turn Only	Not Significant			
	21 **	All Crashes	Not Significant			
		Left-Turn Only	Significant decrease (CMF = 0.79)			
DePauw et al. (2013)	25	All Injury	Significant decrease (CMF = 0.68)	78	All injury	Significant decrease (CMF = 0.62)
		Injury LT	Significant decrease (CMF = 0.54)		Injury LT	Significant decrease (CMF = 0.48)
		All Severe	Significant decrease (CMF = 0.35)		All Severe	Significant decrease (CMF = 0.43)
Schultz et al. (2014)	31	All Crashes	Significant increase (CMF = 1.15)			
		Left-Turn Only	Significant increase (CMF = 1.55)			
Chen et al. (2015)	59	All Crashes	Not Significant	9	All Crashes	Not Significant
		Left-Turn Only	Significant increase (Rate change = 0.3 crashes/2 yrs.)		Left-Turn Only	Significant decrease (Rate change = 0.9 crashes/2 yrs.)

*Intersections where 1 approach was modified

**Intersections where >1 approach was modified

Table 3-5 Effects of Changing a Permissive Left Turn to FYA (Shea et al., 2016)

Study	Permissive to FYA		
	Sites	Crash Type	Effect
Yi (2012)	23	All Crashes	Decrease (-9.0% to -45.0% annual crashes)
Simpson and Troy (2015)	13 (20 approaches) *	All Crashes	Decrease (-6.5% annual crashes)
		LT Only	Decrease (-26.2% annual crashes)
Simpson and Troy (2015)	9 (14 approaches) * FYA permissive only	All Crashes	Decrease (-10.8% annual crashes)
		LT Only	Decrease (-59% annual crashes)

*= Primary changes only included FYA

Table 3-6 Effects of Changing a Protected/Permissive Left-Turn Phase to FYA (Shea et al., 2016)

Study	Protected-Permissive to FYA		
	Sites	Crash Type	Effect
Noyce et al. (2007)	13 *	All Crashes	Decrease (-2.2 annual crashes)
		LT Only	Decrease (-0.9 annual crashes)
McCarroll (2009)	5	LT Only	Decrease (-67.0% annual crashes)
Perez (2010)	2	All Crashes	Decrease (-39.0% annual crashes)
Yi (2012)	20	All Crashes	Decrease (-5.0% to -39.0% annual crashes)
Pulugurtha and Chittoor Khader (2014)	18	All Crashes	Decrease (-39.0% annual crashes)
		LT Only	Decrease (-61.0% annual crashes)
Simpson and Troy (2015)	105 (193 approaches)*	All Crashes	Decrease (-6.6% annual crashes)
		LT Only	Decrease (-22.2% annual crashes)
Schlattler et al. (2016)	90 approaches (with supplemental FYA sign)	All Crashes	Decrease (-8.1% annual crashes)
		LT Only	Decrease (-31.9% annual crashes)
Schlattler et al. (2016)	74 approaches (without supplemental FYA sign)	All Crashes	Decrease (-7.3% annual crashes)
		LT Only	Decrease (-11.5% annual crashes)

*= Primary changes only included FYA

Table 3-7 Effects of Changing a Protected Left-Turn Phase to FYA (Shea et al., 2016)

Study	Protected-only to FYA		
	Sites	Crash Type	Effect
Noyce et al. (2007)	18 *	All Crashes	Increase (0.7 annual crashes)
		LT Only	Increase (1.6 annual crashes)
Perez (2010)	3	All Crashes	Decrease (-15.0% annual crashes)
Yi et al. (2012)	8	All Crashes	Increase (15.0% to 222.0% annual crashes)
Simpson and Troy (2015)	20 (43 approaches) *	All Crashes	Increase (12.0% annual crashes)
		LT Only	Increase (344.0% annual crashes)
Simpson and Troy (2015)	13 (28 approaches) * FYA with TOD operation	All Crashes	Decrease (-10.0% annual crashes)
		LT Only	Increase (1.6 annual crashes)

*= Primary changes only included FYA

It is important to note that several of the studies presented in Table 3-5 and Table 3-6 included changes in addition to FYA installation. An asterisk indicates those studies where the primary changes were FYA installation. Studies that include multiple changes likely exhibit a compounding factor that could alter the results of the study. As such, conclusions should focus more heavily on the studies that involved only FYA installation.

As can be seen in Table 3-5 and Table 3-6, all of the results associated with the studies to examine the effects of changing permissive and protected/permissive left-turn signal phasing to FYA have a decrease in annual crashes between 5.0 percent and 67.0 percent. This includes both the crash type classifications. When considering only studies that do not have compounding factors, the measure of annual crashes has a decrease range between 6.6 percent and 59.0 percent. When the studies that resulted in no significant change are taken into account only eight out of the original 18 study scenarios remain for comparison. When those eight studies are examined, the results show that all of the studies examined involve a decrease in annual crashes.

Table 3-7 presents the effects of changing a protected left-turn phase to FYA based on several studies. Only two of the eight studies in Table 3-7 included intersections that changed more than just the left-turn treatment (Protected to FYA). Of those intersections, only one of the intersections experienced a decrease in the annual crashes. Each of the other studies and related intersections experienced an increase in the number of annual crashes. The increase in annual crashes ranged from 12.0 percent to a 344.0 percent. Specifically, among the three studies that

evaluated left-turn-only crashes in Table 3-7, two experienced an increase of 222.0 percent or higher. Based on this data, it appears that changing protected left-turn signal phasing to FYA can result in a very large increase in left-turn crashes as well as an increase in all crashes.

University of Utah researchers drew the conclusion that the use of a FYA indication generally reduces crash frequency when the left-turn phase is converted from a standard permissive phase or a protected/permissive left-turn indication (see Table 3-5 and Table 3-6) to FYA. Conversely, Table 3-7 shows that conversion from a protected left-turn phase to a FYA increases left-turn crashes.

3.5 Chapter Summary

This chapter summarizes the results of the outreach effort to state DOTs made by the University of Utah research team. This resulted in identifying left-turn policies by state DOTs including the ITE/FHWA Flowchart, the FHWA Guidelines, the State-Adapted Criteria, the Formula-Based Approaches, and No Statewide Guidelines.

In addition to each of the left-turn phasing policies, the safety effects of changing left-turn phasing and the University of Utah's FYA literature review were discussed. The research showed that signal phasing changes from permissive to protected/permissive signal phasing has mixed results meaning an increase or decrease in annual crashes. All of the studies included in the University of Utah's literature review pertaining to changing permissive to protected left-turn signal phasing resulted in a decrease in annual crashes.

The University of Utah concluded that studies have shown that the use of a FYA indication generally results in a reduction in crash frequency or rates when the left-turn phase is converted from a standard permissive phase or a protected/permissive left-turn indication. In comparison, conversion from a protected left-turn phase to a FYA tends to increase the left-turn crashes.

4.0 Literature Review

4.1 Introduction

This chapter contains a summary of four different research reports that were evaluated for the analysis. These include an analysis of variable left-turn phases by time of day, derivation of decision boundaries for left-turn treatments, and two studies on dynamic FYA signal phasing.

4.2 Analysis of Variable Left-Turn Mode Using Left-Turn Delay Prediction Models

This research was completed by Sandesh Chalise, Essam Radwan, and Hatem Abou-Senna from the University of Central Florida (Chalise et al., 2017). One hundred hours of data were collected in Central Florida and used to develop left-turn delay prediction models, while another 100 hours of data were used to validate the prediction model for protected/permissive left-turn phasing. The authors used the microscopic simulation model, VISSIM, to simulate the base scenario and alternative scenario of the protected-only left-turn phase. The study also provides “guidelines to determine the left-turn phase based on the delay and other factors affecting left-turn movement” (Chalise et al., 2017). The author notes that “research has shown that the protected/permitted left-turn control is the most efficient left-turn mode since it allows an extra phase for left-turning traffic and reduces the delay. However, left turns during the permitted phase increase the risk of colliding with oncoming vehicles, because a bad decision might lead to an accident. So, protected-only left-turn control is the safest mode among them. But, PPLT signal control is widely used all over the country because of its efficiency and better operation” (Chalise et al., 2017). Several parameters were taken into account in the research and VISSIM modeling, such as time of day, hour, land use, area type, crossing lanes, permitted green times, permitted left-turn volume, total left-turn volume, left-turn truck percentage, and left-turn delay. A JMP statistical analysis was conducted to validate the model. To summarize the threshold for opposing lanes and the percent reduction in delay created by the model, two scenarios were considered. The first scenario was to evaluate the percent reduction in delay for two through lanes opposing the left turn, the results of which are shown in Figure 4-1. The second scenario was to evaluate the percent reduction in delay for one through lane opposing the left turn, the results of which are shown in Figure 4-2.

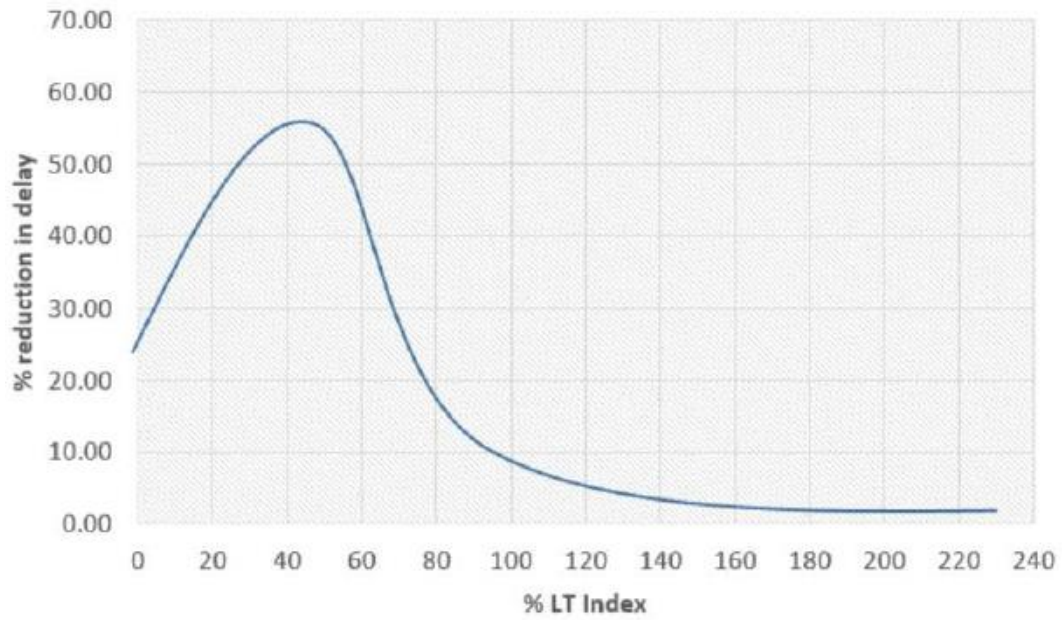


Figure 4-1 Threshold for Two Opposing Lanes (Chalise et al., 2017).

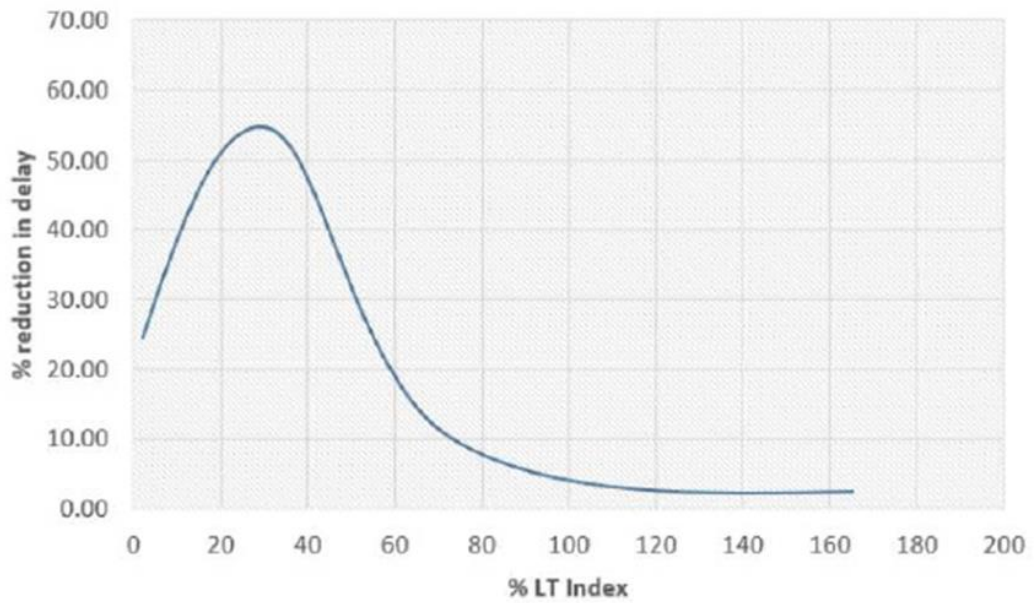


Figure 4-2 Threshold for One Opposing Lane (Chalise et al., 2017).

The Percentage Left-Turn Index (% LT Index), shown in Figure 4-1 and Figure 4-2, is calculated by multiplying the percentage of left-turn volume during permissive time by the percentage of opposing volume during permissive time and dividing that by the percentage of permissive green time in an hour as illustrated in Equation 4-1.

$$\% LT Index = \frac{\left(\frac{PT V_{LT}}{Tot V_{LT}} * 100\right) * \left(\frac{PT V_{OPP}}{Tot V_{OPP}} * 100\right)}{\left(\frac{PT Green Time}{3600} * 1000\right)} \quad (4-1)$$

Where:

$PT V_{LT}$ = Left-Turn Volume during the Permissive Time

$PT V_{OPP}$ = Opposing Volume during the Permissive Time

$Tot V_{LT}$ = Total Left-Turn Volume in vph

$Tot V_{OPP}$ = Total Opposing Volume in vph

$PT Green Time$ = Permissive Green Time in seconds

According to the authors these thresholds can be used to determine the left-turn signal phase for each hour of the intersection. When referring to the phasing choice the authors note that their prediction models are for protected/permissive left turn and protected left-turn phasing. The prediction models that were created can be used to calculate the left-turn delay for each hour and the reduction in percentage delay.

4.3 Derivation of Decision Boundaries for Left-Turn Treatments at Signalized Intersections

This research was completed by Andrew Raessler and Dr. Jidong J. Yang at Kennesaw State University (Raessler and Yang, 2017). The research team outlines a new methodology to establish guidelines for four left-turn treatments including permissive single left turn, protected/permissive left turn, dual protected left-turn lanes with equal lane utilization, and protected dual left-turn lanes with unequal lane utilization. Included in the paper was a benefit and cost analysis using a safety impact, while construction and maintenance costs associated

with different left-turn treatments were also considered. This effectually shifted the boundary curves for more realistic decision making. This research paper focused on evaluating the trade-off or boundary conditions of incremental left turn treatments in order to establish practical guidelines and tools to facilitate decision making on warranting left-turn treatment design options.

As part of the research the authors identified left-turn and opposing volume thresholds for various left-turn treatments. During the research delay points were derived from a Synchro analysis for the scenario comparing a permissive-only single left-turn lane and a protected/permissive single left-turn lane. The average delay (seconds/vehicle) for the permissive-only single left-turn lane option is obtained using Equation 4-2.

$$D_1 = 0.14 * V_{LT}^{.28} * V_{OPP}^{.56} \quad (4-2)$$

Where:

D_1 = Average Delay in seconds per vehicle (sec/veh)

V_{LT} = Left-Turn Volume in vph

V_{OPP} = Opposing Volume in vph

Similarly, the average delay for the protected/permissive single left-turn lane option is obtained using Equation 4-3.

$$D_2 = 0.66 * V_{LT}^{.09} * V_{OPP}^{.46} \quad (4-3)$$

Setting D_1 in Equation 4-2 equal to D_2 in Equation 4-3 and raising both sides of the equation to the power of 7.42, Equation 4-4 is obtained. The value of 7.42 is used to set the product constant to 100,000 for consistency with the product analysis equation (Equation 4-5) in practice.

$$100,000 = V_{LT}^{1.41} * V_{OPP}^{.74} \quad (4-4)$$

$$100,000 = V_{LT}^1 * V_{OPP}^1 \quad (4-5)$$

Equation 4-4 is graphed in Figure 4-3, which is depicted as “Simulated Analysis.” For comparison, representation of the traditional product analysis equation (Equation 4-5) is also graphed and referred to as “Product Analysis” in Figure 4-3.

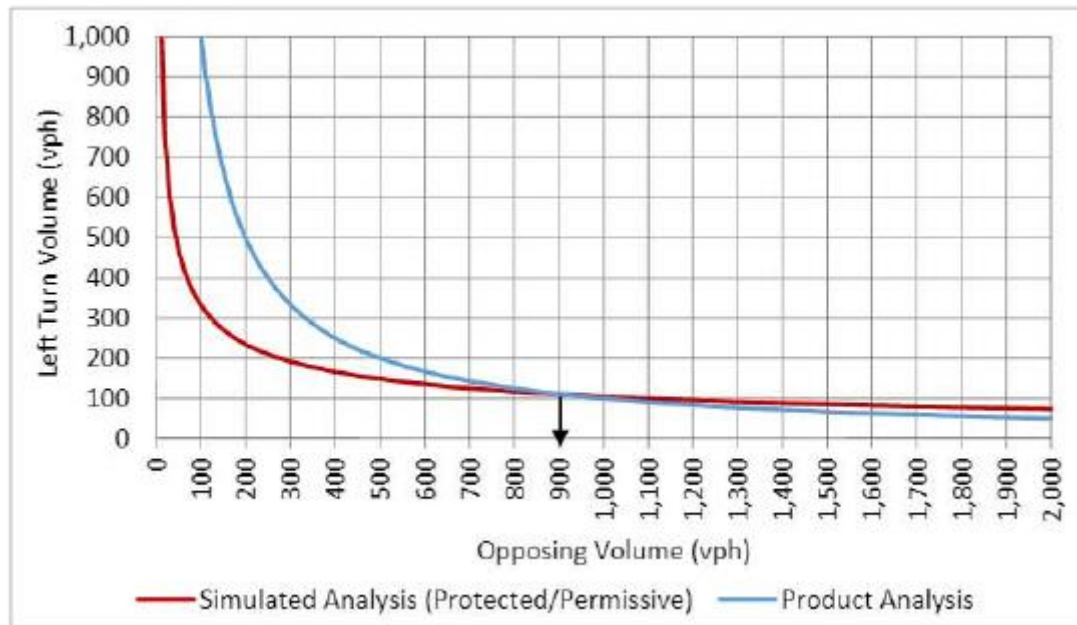


Figure 4-3 Protected/Permissive Versus Permissive-Only Comparison (Raessler and Yang, 2017).

As shown in Figure 4-3, the opposing volumes greater than 900 vph show equivalent delay at higher respective left-turn volumes when compared to the product analysis metric. As a result, a protected/permissive left turn is recommended with slightly higher left-turn volumes given the same opposing volume. At opposing volumes less than 900 vph the research shows equivalent delay at slightly lower respective left-turn volumes when compared to the product analysis metric. Therefore, a protected/permissive left turn is recommended with slightly lower left-turn volumes given the same opposing volume. As seen, the two curves diverge significantly at lower volumes (i.e., less than 500 vph); however, the directional peak hour through volume on the assumed 4-lane roadway section is not expected to be significantly less than 500 vph. Otherwise, it would indicate an oversized roadway for the intended demand (Raessler and Yang, 2017). Several more figures similar to these were developed and explained

in the research paper. All of the data from the research is summarized in Figure 4-4, which can be used in the decision-making process to help choose between different left-turn phasing types based on left-turn volume and opposing volumes.

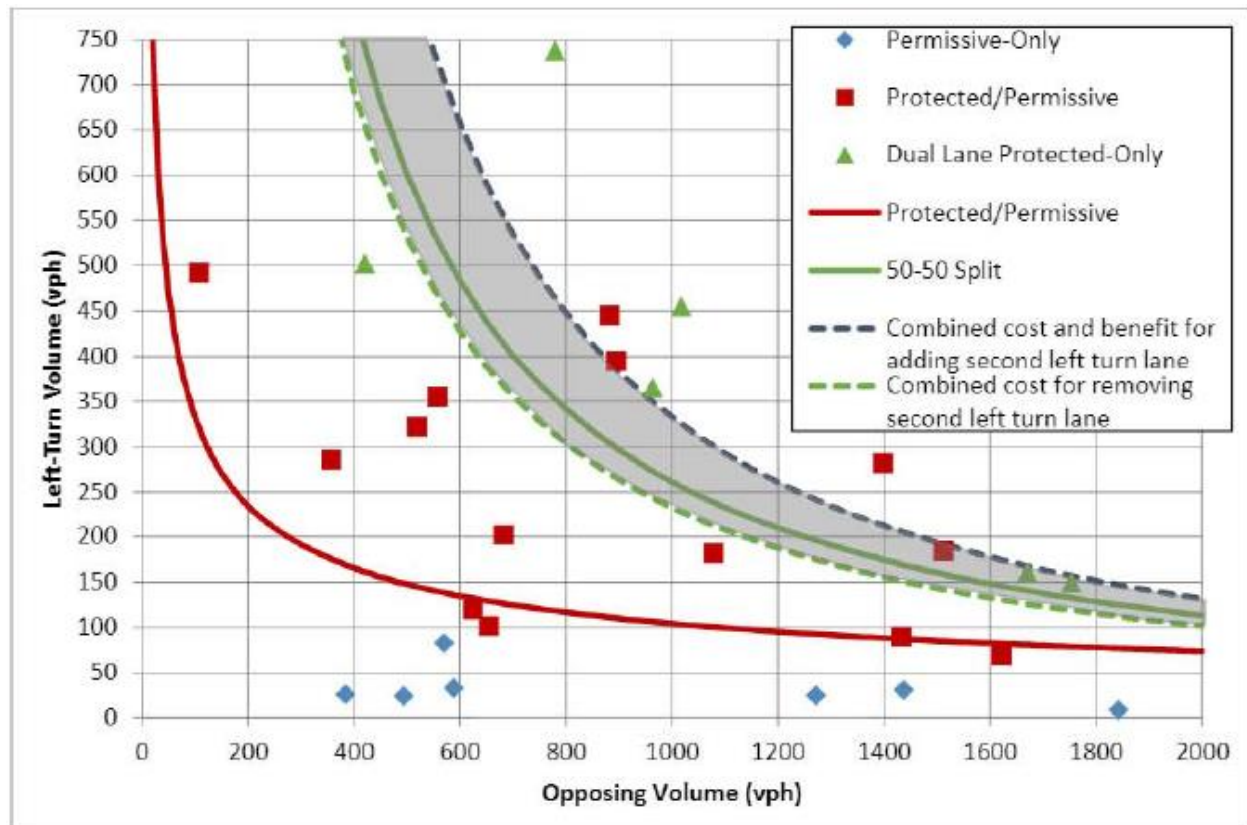


Figure 4-4 Concept Validation Using Existing Configurations and Traffic Counts (Raessler and Yang, 2017).

The points in Figure 4-4 are data from intersections that were used in the research as validation points to establish the reasonableness of the results. According to the researchers “all seven approaches with a permissive-only single left-turn lane (blue diamond) fall in the correct decision region. Of the 14 approaches with a single protected/permissive left-turn lane, represented as red squares, seven approaches fell within the correct decision region. Four approaches fall within the decision region for protected-only dual left-turn lanes, indicating that an additional left-turn lane can be recommended for those approaches. Three approaches fell within the decision region for permissive-only single left-turn lane, indicating that removal of

dual left-turn protection may be recommended. But those three points are very close to the decision boundary” (Raessler and Yang, 2017).

Out of the six approaches with protected-only dual left-turn lanes, represented as green triangles, five fall within the correct decision region. One approach falls in the decision region for single protected/permissive left-turn lane, indicating that downgrading to a single left-turn lane may be recommended for this particular approach. By considering the construction and maintenance costs and safety impact, the revised decision boundaries are shown in dashed lines in Figure 4-4. As shown, the original decision boundary between single protected/permissive left-turn lane and dual protected left-turn lanes is shifted upward when upgrading from single protected/permissive left-turn lane to dual protected left-turn lanes. It is shifted downward when downgrading from protected dual left-turn lanes to protected/permissive single left-turn lane. The shaded wedge area formed by the two shifted curves indicates an inertial region where the existing left-turn treatments should be retained. In other words, any misclassified points based on the original crisp curve (the solid green line) in this area are fine if considering the benefits and costs that would be incurred due to conversion (Raessler and Yang, 2017).

4.4 Dynamic FYA: Variable Left-Turn Mode Operational and Safety Impacts

This research was completed by Essam Radwan, Hatem Abou-Senna, Alex Navarro, and Sandesh Chalise from the University of Central Florida (Radwan et al., 2013). The research addresses the implementation of variable left-turn modes and presents the framework for a decision support system (DSS) for the dynamic evaluation of left-turn phasing in Central Florida. The purpose of this framework is to allow “an interactive evaluation of left-turn phasing and ultimately recommend phasing mode by time of day and Traffic Management Center (TMC) data to be fed into the DSS so that intersections requiring attention/modification of left-turn mode can be flagged” (Radwan et al., 2013).

According to the literature review completed by the research team, many of the developed warrants and guidelines for left-turn treatments are based on either operational efficiency or safety aspects that are tested using benefit/cost analysis or before/after studies. The researchers consider these guidelines to be applicable, but do not consider them to be practical

enough to be implemented in the field. Cross product methodologies were commonly used to analyze left-turn and opposing through volumes for the main warrants. The authors believe that these cross products aren't enough to constitute the entirety of a left-turn warrant system. According to the authors, the data extraction process began with identifying the left-turn approach that would be analyzed. Cameras were set up at the intersections and approaches that were identified for the analysis to record and analyze the intersections and to monitor left-turn parameters related to the volume during the permitted green time. These left-turn parameters were extracted in the laboratory by watching the videos second-by second. Subject left turns were also timed from start to finish on the selected approaches by hand along with the calculation of the critical gap. Conversely, total turning movement counts and gap analysis were processed at the intersections using automated video detection. Across all of the intersections, 23 left-turn approaches were analyzed totaling 229 hours of video data processed including off-peak and peak conditions. The authors described how the video data extraction was an essential process in constructing and analyzing the design of the experiment and eventually developing the new thresholds for the determination of left-turn modes by time of day (Radwan et al., 2013).

The research team used JMP statistical software to mathematically optimize the left-turn criterion. Generalized Linear Models were specifically used in the JMP statistical analysis. The developed Poisson regression model provided better prediction profiles and showed the relationship between the significant parameters to a third-degree polynomial equation with coefficient of determination ($R^2=0.84$). JMP has an interactive capability of fitting a separate prediction equation for each dependent variable, such as volume or speed, to the observed response (protected left-turn volume). This enables prediction of all combinations of parameters on the dependent variable at the same time. The analysis of the experiment produced an interactive DSS for left-turn mode. Based on the predicted number of left turns during the permitted phase, the analyst can determine whether the permitted left-turn phase is feasible or not. Three criteria were developed for this particular decision, two of the criteria are related to operational aspects while the third one relates to safety. Specific thresholds were also determined for these criteria. The purpose of the system is to dynamically determine the mode of the left turn for the particular intersection using the aforementioned criteria and thresholds (Radwan et al., 2013).

4.5 Dynamic FYA: Variable Left-Turn Mode Operational and Safety Impacts Phase II

This research was completed by Essam Radwan, Hatem Abou-Senna, Hesham Eldeeb, and Alex Navarro from the University of Central Florida (Radwan et al., 2016). The research addresses time-of-day traffic modeling simulations for FYA. The authors intend on using the FYA signal as a variable mode that can be changed on demand. The first phase of this research developed a DSS that facilitated the selection of the FYA left-turn mode, changing by time of day at intersections (Radwan et al., 2013). The purpose of this, the second phase of the Dynamic FYA research, was to demonstrate the ability to execute the automation of the process. The algorithm developed by the research team was implemented with the goal of safely optimizing traffic operations with constant analysis in real time to determine whether it would be optimal to switch the red arrow to an FYA. The algorithm determines the time interval between the successive arrivals of vehicles and computes the corresponding headway for each lane by cycle on a second-by-second basis.

The database for this project was increased to 38 intersections throughout the state of Florida for the second phase. The data included in the analysis was required to have a balanced number of peak and off-peak conditions. According to the researchers, the model provided a high correlation between independent variables with a coefficient of correlation reaching 90 percent. The DSS was tested at two different intersections in Seminole County. The testing confirmed the applicability and validity of the developed DSS. The purpose of this system is to “provide traffic engineers with the tools to utilize the efficiency of the permissive left turn at peak and off-peak times. In turn, this can reduce the delay at approaches when there are low volumes on the roadways. The FYA 4-section configuration provides the opportunity for a fully adjustable system and provides the Traffic Management Centers (TMCs) with more tools to operate the intersections as efficiently as possible” (Radwan et al., 2016).

The algorithm developed in the research is used to analyze the opposing through traffic on a constant basis to determine the minimum headway of vehicles, the number of lanes to cross, and the number of cycles to be analyzed prior to making a decision. It is used to calculate the time interval between successive opposing vehicles for each lane and to compute the headway for each lane by cycle. Using this headway, the gap per lane is calculated by dividing the

headway by the flow. The algorithm is then used to identify the minimum headway that can be compared to the minimum acceptable gap in seconds needed for a vehicle to safely cross the given number of lanes. The thresholds used for different crossing number of lanes were obtained from the database of 30,000 cycles collected from the field. If the minimum headway for the corresponding number of lanes is achieved and repeated for a certain number of times, for example, at least five times during the analysis period (whether one or two cycles) which is also an input to the algorithm, the decision is made to switch to a flashing yellow mode. Otherwise, a red arrow is selected. The gap time in seconds, shown in Table 4-1, is the minimum acceptable threshold used to determine the minimum headway for different number of lanes crossed which are used in the decision-making process. Depending on the needs of the intersection, a state DOT may be able to adapt this algorithm to their own needs and desires.

In a personal communication with Dr. Hatem Abou-Senna it was learned that the second phase of the research included offline field tests. The research team is currently (as of April 2017) working on the third phase of this project. After the third phase has been completed, the Florida Department of Transportation (FDOT) will implement their DSS online. According to Dr. Abou-Senna the third phase of the project is tentatively scheduled to be completed by the end of 2018 (Abou-Senna, 2017).

Table 4-1 FYA Algorithm Criteria (Radwan et al., 2016)

No. of Opposing Lanes Crossed	Min Acceptable Gap Time	Comments
1 Lane	3.0 s.	1 Through Lane
2 Lanes	3.5 s.	2 Through Lanes or 1 Through + 1 RT
3 Lanes	4.0 s.	3 Through Lanes or 2 Through + 1 RT
4 Lanes	4.5 s.	4 Through Lanes or 3 Through + 1 RT

4.6 Chapter Summary

Each of the four research papers summarized in this chapter can be used in the future development and discovery of techniques to improve the safety and operations of traffic in the state of Utah. Each research topic shows potential for being implemented in some degree or another, and each warrant is being considered as part of future research efforts.

Raessler and Yang's research paper aimed to evaluate the trade-off or boundary conditions of incremental left-turn treatments in order to establish practical guidelines and tools to facilitate decision making on selecting left-turn treatment design options, this is one of many tools that UDOT could consider looking into as a basis of future left-turn warrant analysis. While Raessler and Yang's research shows a lot of potential for future improvement, the research being conducted by the University of Central Florida on DSS could be extremely beneficial. The system, as it is designed, would allow traffic engineers to make time-of-day traffic modeling simulations for FYA. From the research, it appears that the authors intend to use the FYA signal as a variable mode that can be changed on demand, which could be very useful for state traffic engineers.

5.0 State of Practice

5.1 Introduction

To better understand left-turn warrant procedures across the nation, a state of practice survey was conducted by the research team that included a survey of different states, cities, and counties with regards to their individual left-turn warrants and practices. The research team created two different surveys to optimize the survey results and to minimize effort for responding agencies. The first survey, titled FYA Survey, was prepared for the purpose of surveying states who already responded to the University of Utah survey discussed previously in Chapter 3 and was used to supplement the data provided previously by obtaining information regarding FYA best practices. The second survey, titled Left-Turn Signal Warrant Study + FYA Survey, was prepared for states who did not respond to the University of Utah survey, as well as cities and counties recommended by the Technical Advisory Committee (TAC) to obtain information regarding general left-turn phasing policies and FYA best practices. Each of the surveys is discussed in this chapter. The full list of survey questions is provided in Appendix C.

5.2 FYA Survey

The first survey distributed by the research team was prepared for state agencies that already responded to the University of Utah survey discussed previously in Chapter 3. This survey only had questions regarding FYA warrants and installations, time-of-day signal phasing, and policy regarding the change of signal phasing (i.e., how and when does the state determine if traffic signal phasing should be changed). Because the survey was a continuation of the University of Utah survey, this survey was distributed to representatives from all 50 states with the exception of the six states who did not respond to the initial survey conducted by the University of Utah. The survey was distributed to 167 different contacts on Monday April 24, 2017. The research team felt that it would be appropriate to distribute the survey to multiple contacts within each state in order to increase the probability of receiving a response from every state included in the survey. There were a total of 38 responses to the survey, with responses from 32 different states. For those states that provided multiple responses, the responses were reviewed for consistency. The following subsections provide a summary of the survey results,

the warrant and guidelines obtained, time-of-day signal phasing, information regarding re-evaluating signal phasing, and additional literature related to the topic.

5.2.1 FYA Survey Results

Table 5-1 provides a summary of the FYA survey results including a list of all the states that utilize FYA, the states that do not utilize FYA, states that include FYA in their protected/permissive warrants and guidelines, states that utilize time-of-day signal phasing, and states that have warrants and guidelines for time-of-day signal phasing. It should be noted that some states are listed in the table more than once. This is due to columns three through five being subsets of the first two columns. Column three is specifically a subset of the first column while columns four and five are subsets of both columns one and two.

Of the responding agencies, there were four states that do not utilize FYA: Connecticut, Delaware, Hawaii, and Ohio. While these states noted that they do not utilize FYA, representatives from their respective agencies were still able to provide insight into time-of-day signal phasing practices as well as policies regarding the changing of signal phasing.

5.2.2 Warrants and Guidelines Results

There were a total of 32 states that responded to the FYA survey, of which 28 utilize FYA. Out of the 28 states that utilize FYA signal phasing only 16 states (57 percent) have formal warrants or guidelines. Each state that has a formal left-turn warrant or guideline has a methodology of choosing which type of signal phasing is warranted including the ITE/FHWA flowchart, FHWA guidelines, state adapted criteria, or a formula based approach as outlined in Chapter 3. Each of the states that utilize FYA but do not have specific statewide warrants or guidelines make decisions based on engineering judgment on a case by case basis.

Based on the survey results summarized in Table 5-1, all 16 states that have their own FYA warrants and guidelines lump their FYA warrants and guidelines in with protected/permissive signal warrants and guidelines. While all 16 states include FYA in their protected/permissive warrants, each state has a different methodology of determining how to warrant a protected/permissive left turn, as outlined previously in Chapter 3.0. Each state also

has a different method of displaying the FYA based on the intersection. As a result, each of the FYA warrants are a subset of the existing warrants for each state.

Table 5-1 Summary of the FYA Survey Results

States that Utilize FYA (28 States)	States that Do Not Utilize FYA (4 States)	States that include FYA in their Protected/Permissive Signal Phasing Warrants (16 States)	States that Utilize Time-of-Day Signal Phasing (16 States)	States that Have Warrants / Guidelines for Time of Day (5 States)
(1)	(2)	(3)	(4)	(5)
Alabama Alaska Arizona Arkansas Florida Idaho Illinois Indiana Kentucky Louisiana Maine Massachusetts Minnesota Mississippi Nebraska Nevada New York North Carolina Oklahoma Rhode Island South Carolina South Dakota Tennessee Texas Vermont Virginia Washington Wisconsin	Connecticut Delaware Hawaii Ohio	Alabama Alaska Illinois Indiana Kentucky Massachusetts Minnesota Mississippi New York South Carolina South Dakota Tennessee Texas Vermont Virginia Washington	Alaska Arkansas Delaware Florida Indiana Kentucky Minnesota Mississippi Nebraska New York North Carolina Texas Vermont Virginia Washington Wisconsin	Indiana Minnesota Mississippi Vermont Washington

*Non-Responding States: Georgia, Iowa, Kansas, Michigan, Missouri, New Hampshire, North Dakota, Oregon, Pennsylvania, Wyoming

The University of Utah survey, discussed previously in Chapter 3, noted that there were states that had specific warrants and criteria for protected/permissive signal phasing. Utah has their own volume cross product guidelines as shown previously in Table 2-1 and Table 3-2 to specify the volumes that would warrant a protected/permissive signal phase. As shown in Table 3-2 there are other states that have their own warrants and guidelines on the volume thresholds that should be used to choose between a protected/permissive or protected-only signal phase. The survey conducted for this research found that the majority of states that answered the survey utilize FYA and have their own set of warrants or guidelines for FYA use. It was common to find among the answers to the survey that when protected/permissive signal phasing is being used, the permissive portion of the signal phase is carried out using FYA. While these 16 states have made FYA part of their protected/permissive warrants and guidelines, there are some states that have decided to include FYA as part of their permissive signal phasing warrants and guidelines as well. Massachusetts, South Carolina, Texas, Tennessee, Virginia, and Washington allow for the use of FYA during permissive signal phasing meaning that the normal green signal used in a permissive phase is replaced with a FYA signal head.

5.2.3 Time-of-Day Signal Phasing

As shown in Table 5-1, there were a total of 16 states (50 percent of those responding) that utilize time-of-day signal phasing. Of those 16, only 5 states have set warrants or guidelines for time-of-day signal phasing. Each state has their own method of determining what portions of the day warrants a specific signal phasing. Indiana, for example, uses a left-turn signal display worksheet that analyzes peak hours, the average daytime values, and the average nighttime values for specific criteria such as sight distance, traffic volume, the number of lanes, opposing speed limit, and the number of left-turn crashes. Based on the values of each one of these criteria a risk level (e.g., low, normal, or elevated) is assigned. The Indiana Department of Transportation (INDOT) operations memorandum 15-04 states the following (INDOT, 2015):

- 1) If upon completing the display worksheet only one of the analysis criteria indicates a normal risk and the rest of the criteria indicate a low risk, the permissive only signal display may be selected based on engineering judgment.
- 2) If two or more of the analysis criteria indicate a normal risk for the left turning vehicles at the location, the left-turn signal display is typically protected/permissive.
- 3) If only one of the analysis criteria indicates an elevated risk for left-turning vehicles, the District Traffic Engineer may select the protected/permissive signal display based on engineering judgment.
- 4) If two or more of the analysis criteria indicate an elevated risk for the left-turning vehicles at the location; the left-turn signal display is typically protected only.

A blank left-turn signal display worksheet used by INDOT is provided in Appendix D. Each time of day that is analyzed using this worksheet can be assigned as permissive, protected/permissive which includes FYA, or protected-only signal phasing.

Vermont uses the flowchart in the FHWA Signal Timing Manual created by ITE which was shown previously in Figure 3-1. The flowchart is used by engineers in the state of Vermont specifically with their left-turn warranting process to determine if the intersection in question warrants permissive, protected/permissive which includes FYA, or protected-only signal phasing. According to representatives from Vermont the peak hours will often have protected-only signal phasing while non-peak hours will have protected/permissive signal phasing.

Some states, including Minnesota, have a set of questions in a flowchart that have to be answered in order to implement a protected/permissive or protected-only signal phasing. Examples of questions used include:

- Do the opposing left-turn paths conflict?
- Does the left-turn driver have very limited sight distance as defined in the current American Association of State and Highway Transportation Officials (AASHTO) *A Policy on Geometric Designs of Highways and Streets*?

- Does the left-turn lane have two or more lanes?
- Is protected/permissive operation in place and is there a high number of left turn crashes during the time period in question over an X-year period susceptible to correction by protected-only phasing?
- Is the speed X mph or greater and the peak hour left-turn volume greater than X vph or is the peak hour cross product greater than X (Y if two opposing lanes)?

The specific values have been removed from the questions above to illustrate how a state would set these questions up for their own use. While these questions are used specifically in their overall warranting process, they can be used on an hour-to-hour basis to establish if certain times of the day warrant a safer signal phasing.

Mississippi guidelines regarding time-of-day signal phasing are the same as their left-turn warranting process. Intersections are analyzed using the state's warranting procedures for each hour of the day. If the protected-only warrants are met, as shown previously in Table 3-2, during the peak hours, but not during other parts of the day, then time-of-day signal phasing is implemented and protected-only is used during the peak hours and protected/permitted is used during off peak.

5.2.4 Re-evaluating Signal Phasing

It was determined from the survey results that out of the 32 states that responded to the survey, 13 states noted that their state has a specific policy on re-evaluating signal phasing based on various changes in traffic and signal conditions. Those states include: Alaska, Arkansas, Indiana, Kentucky, Louisiana, Massachusetts, Minnesota, New York, Rhode Island, South Dakota, Tennessee, Texas, and Virginia. Each state has a policy that the intersection and signal phasing in question be re-evaluated using the state's warranting policy. For example, the state of Alaska uses the ITE/FHWA flowchart to determine the type of signal phasing that should be used at an intersection. After the intersection has been chosen to have its signal phasing re-evaluated the intersection is re-examined using the ITE/FHWA flowchart during a formal traffic study. The specific reasons why an intersection's signal phasing might be re-evaluated vary slightly from state to state; however, almost all of the states noted that decisions to re-evaluate

the signal phasing of an intersection generally comes from citizen complaints, safety concerns, a significant change in traffic volumes, and/or a change in the roadway or signal phasing network in the surrounding area.

There were a small number of states that gave the research team additional information about the subject of re-evaluating signal phasing even though their respective states do not have a formal policy. The states of Alabama and Wisconsin specifically stated that their states are in the process of creating one. Additionally, both of those states specified that they currently have a common practice similar to the one described in the paragraph above where the intersection in question is evaluated using the state's warranting procedures and guidelines. Several other states mentioned that they do not have a specific policy on the matter but that the state leaves these decisions to engineering judgment.

5.2.5 Potential Future Literature

While conducting the FYA survey the research team was made aware of a future research project to be conducted by Dr. Ali Hajbabaie at Washington State University. The research project is entitled *A Data Driven Safety Assessment of Various Left-Turn Phasing Strategies*. According to the research proposal that was given to our team the objectives of the research include: 1) comparing the safety of protected left turns to protected permissive left turns with FYA, 2) comparing the safety of doghouse displays to four section vertical displays with FYA, and 3) assessing the safety of including FYA phases in protected/permissive left turns at different times of the day to identify if it creates driver confusion. The benefits outlined in the proposal include identifying the safety and operational performance of various left-turn phasing sequences. The project will provide the Washington State DOT with guidance on left-turn phase sequence selection in response to various operational and safety conditions. Their research efforts will also include crash data collection and analysis as well as simulation based assessment of operational impacts. According to the research proposal "A set of simulation runs will be made to evaluate the impact of different phasing strategies on traffic operations. It should be noted that the impact of different signal faces on safety cannot be evaluated in a simulated environment; however, we can compare the operational effects of protected left turns, and protected-permissive left turns. The team will study a number of performance measures such as

control delay, average travel time, queue length, and saturation headway for different phasing strategies” (Hajbabaie, 2017). According to the research proposal the research is currently scheduled to be completed by December 31, 2017.

5.3 Left-Turn Signal Warrant Study + FYA Survey

The second survey was prepared for state agencies that did not respond to the University of Utah survey, discussed previously in Chapter 3, as well as cities and counties recommended by the TAC. This survey includes all of the questions from the previous survey as well as questions regarding left-turn warrants that were adapted from the original University of Utah survey. The six states that did not respond to the initial survey conducted by the University of Utah include California, Colorado, Maryland, New Jersey, New Mexico, and West Virginia. The TAC members also recommended that the survey be sent to representatives from the cities of College Station, Dallas, and Richardson, TX; Las Vegas and Clark County, NV; Seminole County, FL; the cities of Anaheim and San Jose, CA; the city of Kennewick, WA; and the city of Portland, OR. The survey was distributed to 53 different contacts on Monday April 24, 2017. Out of the 53 different contacts that the survey was sent out to there were only four complete responses. The agencies that fully completed the survey include the city of Portland, Seminole County, the city of San Jose, and the Regional Transportation Commission of Southern Nevada. There were two other incomplete responses from Clark County Nevada and the California Department of Transportation (CalTrans). A detailed description of the findings from each of the four respondents is provided in the following sections.

5.3.1 City of Portland, Oregon

The city of Portland, Oregon follows the guidelines and warrants set forth by the Oregon DOT which were summarized in Chapter 3. Because the city of Portland follows the state guidelines regarding left-turn signal phasing only the warrants and guidelines regarding FYA will be discussed in detail. FYA warrants for the city of Portland are similar to many of the states that responded to the FYA survey in the sense that the FYA warrants and guidelines are part of the protected/permissive warrants. The volume cross product that the state of Oregon uses was shown previously in Table 3-2. The city of Portland allows for time-of-day signal

phasing. Protected-only signal phasing is often used during peak hours of the day while protected/permissive left-turn signal phasing is used the rest of the day. To determine if this practice can be implemented at a particular intersection an analysis of the intersection has to be conducted for the time of day in question to determine the type of signal phasing needed. According to the survey response the city of Portland prefers to use protected/permissive signal phasing throughout the day and use protected-only signal phasing during the peak hour as needed.

5.3.2 Regional Transportation Commission of Southern Nevada

The Regional Transportation Commission (RTC) of Southern Nevada follows the guidelines and warrants set forth by the Nevada DOT with regards to left-turn signal warrants. The left-turn warranting process followed by the state of Nevada was summarized previously in Chapter 3. According to the survey, the RTC of Southern Nevada maintains communications to signals and signal databases for five agencies; the City of Las Vegas, the City of North Las Vegas, the City of Henderson, Unincorporated Clark County, and the State of Nevada. The cities included in this jurisdiction utilize FYA, but specific warrants and guidelines do not exist. The RTC recommends that protected-only signal phasing be utilized during peak hours of the day. Protected/permissive signal phasing can be utilized during other parts of the day. In the survey response, the RTC specifically stated that “permissive signal phasing is recommended for overnight or very light traffic times in order to shorten cycle times when coordinated or free.” According to that same response the current thinking within the valley is to examine all signalized single lane left turns where the speed limit is under 45 mph to evaluate whether FYA would enhance operational efficiency.

5.3.3 Seminole County, Florida

Seminole County, like the other cities that responded to this survey, uses the guidelines and warrants that have been established by the state DOT with regards to left-turn signal warrants. The different warrants and guidelines that the state of Florida uses can be found in Chapter 3, the left-turn volume matrix can specifically be found in Table 3-2. The major difference between Seminole County and the other cities who responded is that the county utilizes both FYA and time-of-day signal phasing, but does not have specific warrants or

guidelines. These types of decisions are left to engineering judgment after completing a traffic study.

5.3.4 City of San Jose, California

The City of San Jose representative indicated that while different left-turn signal phasing methods are used there are no set guidelines. In the survey response, it was reported that correctable crash data are used to prioritize funding for left-turn warrant studies and signal phasing changes. It was noted that a volume of 200 veh/hr is often used as a trigger for providing a left-turn pocket and signal control at intersections. While dual left turns may be used in other parts of the state of California, the city of San Jose does not allow dual left-turn lanes. In addition, FYA is also not permitted in the city, therefore there are not any warrants or guidelines related to FYA installation. The city also does not utilize time of day signal phasing and does not have a policy on re-evaluating signal phasing at intersections.

5.4 Chapter Summary

Based on the findings of the synthesis of practice survey it can be concluded that where FYA warrants and guidelines exist, they are similar. All states that have specific warrants and guidelines regarding FYA use the state DOTs protected/permissive signal phasing warrants and guidelines. As discussed in Chapter 3, there are several different methods of conducting a left-turn warrant analysis including: ITE/FHWA Flowchart, FHWA guidelines, state-adapted criteria from ITE and FHWA guidelines, and formulaic set of criteria. While there are differences in the warrants for protected/permissive signal phasing between the various states, the states that answered the survey for this research indicated that FYA is uniformly included as part of the protected/permissive warrants and guidelines.

Regarding time-of-day signal phasing, there were a total of 16 states (50 percent of respondents) that utilize time-of-day signal phasing. Only 5 of the 16 have set warrants or guidelines for time-of-day signal phasing. The state entities analyze the different times of day to find if a certain signal phasing can be warranted during those hours. Often, these states prefer to use protected/permissive signal phasing during off-peak hours of the day and protected-only signal phasing during the peak hours of the day.

6.0 Limited Recommendations for Further Research

6.1 Introduction

The purpose of this chapter is to provide limited recommendations based on the findings in this report. Topics that will be addressed in this chapter include analysis of decision boundaries for left-turn treatments, changing the volume criteria, time of day and FYA warrants, and a record of decision making.

6.2 Analysis of Decision Boundaries for Left-Turn Treatments

In the 2017 Utah Transportation Research Advisory Council (UTRAC) Workshop UDOT approved a research problem statement that can be used as a continuation of the information that is presented in this report. According to the research problem statement authored by Dr. Grant Schultz and Dr. Mitsuru Saito, the topic of left-turn phasing is not new to UDOT and a variety of projects have been conducted recently (or are ongoing) to evaluate safety of left-turns as well as to evaluate the warranting of left-turn phasing. There is a need to better understand the safety and operational effects of left-turn phasing and to identify boundaries for left-turn treatments at signalized intersections based on actual data from across the state. The purpose of the proposed research is to evaluate the mixture of left-turn and opposing through traffic volumes for permitted vs. protected left-turn phasing at intersections and to identify cut-off points as a result of the data that would help to identify when to switch from permissive to protected phasing at intersections, as well as when to transition from single to dual left-turn facilities. It is anticipated that would be done using the signal performance measurement data combined with the safety crash database to correlate operations and safety. Because of the randomness of crash data and potential limits to the data that are available, it is recommended that the field measured data be supplemented with simulation data using VISSIM and the Surrogate Safety Assessment Model (SSAM) developed by FHWA. This will allow the research team to control the left-turn volume and opposing traffic volume levels to aid in determining meaningful boundaries for the different left-turn treatments. Practical guidelines need to be established to evaluate permissive single left-turn lanes, protected/permissive single left-turn lanes, and protected single and dual left-turn lanes.

Within this proposal three objectives are outlined:

- 1) Evaluate left-turn phasing as a function of operations and safety.
- 2) Evaluate the mixture of left-turn and opposing through traffic volumes for permitted vs. protected left-turn phasing at intersections using both field measurements and simulation data.
- 3) Identify cut-off points as a result of the data that would help to identify when to switch from permissive to protected phasing at intersections, as well as when to transition from single to dual left-turn facilities.

It is possible that this research project will include curves or figures similar to research conducted by Andrew Raessler in association with Dr. Jidong J. Yang, with Kennesaw State University, that were shown previously in Figure 4-3 and Figure 4-4. Figure 4-3 summarizes the results regarding permissive-only vs. protected/permissive single left-turn lanes. Figure 4-4 can be used in a decision-making process to help choose between different phasing types based on left-turn volume and opposing volumes. UDOT will benefit from this research by gaining an understanding of possible boundaries that could be used to identify when to install specific combinations of permissive vs. protected left-turn phasing in the state. The results of the research would help UDOT to identify possible changes and new recommendations on left-turn operations that would help to meet both the safety and operations goals of the department. It is recommended that this research be completed and applied to the current left-turn signal warrant guidelines and policies.

6.3 Comparisons of Volume Criteria and Potential Future Research Opportunities

In a memorandum submitted to UDOT by Hales Engineering it was noted that concern has been raised with regards to the volume cross product thresholds being too low, resulting in left-turn phasing being implemented too often, or at intersections where it is not truly needed. This section of the report addresses this topic by comparing left-turn volume criteria to other states and agencies. The comparison of left-turn volume cross products by state will be followed

by the feasibility of increasing the volume cross product to include right-turn vehicles. Finally, future research regarding left-turn volumes will be addressed.

6.3.1 Comparison of Left-Turn Volume Cross Products by State

Utah is not the only state to utilize state-adapted versions of the FHWA or HCM volume cross products in their warranting procedure. As previously shown in Table 3-2 there are 13 states besides Utah that have state-adapted criteria for their volume cross products. Each of these 14 states has a slightly different method of evaluating volume cross products and each has different values that are used. Some states have their cross products differentiated by urban and rural settings (Arizona and Mississippi) while others have their cross products differentiated by the type of arrival, such as random or platooned (Utah and Vermont). The remaining 10, of the 14 total, states do not use either of these differentiators.

When comparing Utah's cross product volumes with each of the different states in Table 3-2 there are three states that have larger cross product volumes than Utah while comparing their volumes to the random arrival including: Arizona (urban only), South Carolina, and Ohio. The rural cross product values for Arizona are lower than Utah's random arrival values. Utah's platooned arrival has higher values than its random arrival, and as a result only Arizona's urban volume cross product, the South Carolina and Ohio volume cross products, for one opposing lane, exceed Utah's platooned arrival. It should be noted that while South Carolina's volume cross product exceeds Utah's it is because South Carolina does not specify a volume-based on the number of opposing lanes. As a result, the number that South Carolina gives is larger than the value given for only one opposing lane. Similarly, Ohio's volume cross product for one opposing lane exceeds Utah's, but does not exceed Utah's two lane cross product volume.

There are a total of six states that have the same volume cross product values as Utah's random arrival. The platooned arrival exceeds all those states due to its larger thresholds. There are two states, Arizona and Tennessee, that have specific volume thresholds for three opposing lanes that allow for higher thresholds. Arizona uses 50,000 for one opposing lane, 100,000 for two, and 150,000 for three opposing lanes in rural settings, while using 75,000 for one opposing lane, 150,000 for two, and 225,000 for three opposing lanes in urban settings. The state of Arizona does require that protected-only left turns be used for intersections with three opposing

lanes. Tennessee uses 50,000 for one opposing lane, 90,000 for two, and 110,000 for three opposing lanes.

Utah has one of the highest cross product volumes of any state. The volumes may not need to be changed or restructured, but future research can and should be conducted in order to optimize the volume cross products for the state of Utah. This research can test the effects on both operations and safety aspects of increasing or decreasing the volume cross products in order to determine if there are positive effects of changing the volume cross product thresholds. Additional research can help identify if a change or restructuring of volume cross product thresholds is needed.

The research team has identified two different recommendations that can be considered in future research regarding the change or restructuring of volume cross product thresholds. The first of these recommendations is that distinct values should be considered separately for intersections with two and three opposing lanes. It is recommended that this be further studied to determine the safety and operational impacts of such a change.

The second recommendation is that if UDOT were to consider changing the current volume thresholds without changing the current structure of the volume cross product, meaning that two and three opposing lane thresholds remain the same, then more research and modeling needs to be conducted. Utah already has some of the highest threshold values in comparison to other states that have their own state adapted criteria, but the thresholds could be changed (increased or decreased) if specific research shows a positive impact. The research team recommends that more research and modeling be conducted to determine the safety and operational impacts of raising or lowering the threshold values without changing the current structure.

6.3.2 Inclusion of Right-Turning Vehicles in the Volume Cross Product

Another critical element for consideration is the presence of a right-turn lane, as well as the inclusion of opposing right-turn lane and pedestrian volume in the volume cross product. Currently the opposing right-turn and pedestrian volumes are not included in the volume cross product. According to a memorandum to UDOT by Hales Engineering, it may be beneficial to

include right-turn movements in the warranting process because the presence of right-turning vehicles, as well as pedestrians, influence the decisions of those drivers that are turning left at an intersection. According to their report, peak-hour turning count data from 32 of the most recent left-turn studies completed at the time by UDOT Traffic and Safety throughout the state was compiled. The proportion of right-turning vehicles to through vehicles was calculated based on the number of through lanes on each approach. The results of the peak hour turning movement count data can be seen in Table 6-1 (Hales Engineering, 2016).

Table 6-1 Proportion of Right-Turning Vehicles to Through Vehicles (Hales Engineering, 2016)

Number of Through Lanes	% of Right Turns
1	42%
2	11%
3	14%

One alternative, outlined by Hales Engineering, for including opposing right-turn vehicle volume in the volume cross-product calculations would be to increase the thresholds of the cross product proportionally to the percent of right turns. When the right-turning vehicles are added to the calculations, the volume cross-product could be increased by 40 percent for approaches with one through lane, and by 12 percent for approaches with two or three lanes (the average of the percentage of right-turns for the two scenarios). The potential volume cross product thresholds are shown in Table 6-2, assuming a proportional increase (Hales Engineering, 2016). This represents one alternative on how the left-turn phasing thresholds could be modified if right-turn volumes are included in the cross-product calculation. It is recommended that more analysis be done on the volumes before selecting the percentages. Research should be conducted to examine the distribution of right-turns and determine the impact of including the right-turn volumes. The percentages outlined here are to be considered an example of a methodology that could be used.

Table 6-2 Potential Increase to UDOT Left-Turn Phasing Thresholds if Right-Turns are Included (Hales Engineering, 2016)

Potential Increase to UDOT Left-Turn Phasing Thresholds			
Number of Opposing Lanes	Volume Cross Product		
	Random Arrivals	Platoon Arrivals	% Increase
1	70,000	84,000	40%
2 or 3	112,000	135,000	12%

If the change to the volume cross product to include the percentage of right-turning vehicles was included, then the accuracy of the left-turn warrant procedure currently utilized by UDOT could be increased to match the field conditions of the intersection being analyzed. The inclusion of right-turn volume at intersections in the warranting process may or may not impact operations and safety. The effects would need to be identified and then analyzed using modeling software such as Synchro, VISSIM, and/or SSAM to determine if overall these changes would positively or negatively impact the operations or safety of the intersection in question.

Another condition that would need to be investigated is the difference between intersections that have exclusive right turn pockets and intersections that have right turn movements and thru movements in the same approach lane. This condition is commonly referred to as a thru-right lane because the lane configuration allows for vehicles to move straight through the intersection or turn right while utilizing the same lane. It is possible that operational and safety differences would exist between the two different scenarios. The difference in operational and safety impacts between the two different lane configurations could potentially impact the decision on whether or not to include right-turning vehicles in the volume cross product criterion as they currently exist. This would need to be researched more thoroughly before being considered for implementation by UDOT.

The Region Traffic Operations Engineering and Traffic Policy Committee has been involved in investigating whether or not the existing cross product threshold criteria are acceptable. Further research in this area would potentially benefit the committee and influence future traffic operations related decisions in the future. Based on the memorandum provided by Hales Engineering in 2016 the committee decided not to move forward with researching the impact of including right-turning vehicles and pedestrians. Future research in this area would

provide more information on the impacts on operations and safety caused by the inclusion of right-turning vehicles. The Region Traffic Operations Engineering and Traffic Policy Committee would then be able to determine if these changes should be implemented or not based on the data provided. A state by state comparison of left-turn volume thresholds cannot be made at this time because data on left-turn volume thresholds were not included in the surveys conducted. The volume data that were made available was given in the form of a volume cross product which was previously analyzed. Future research should include an investigation into the practices of other states regarding left-turn volume thresholds.

6.4 Time-of-Day and FYA Warrants

One of the topics addressed in the research was the practices that other cities and states use for time-of-day signal phasing. The practice of analyzing intersections by time of day to determine which signal phasing is warranted should be further researched to determine if it is a feasible option for the state of Utah to adopt. Part of this research should include the creation of a formal set of guidelines to provide a basis for traffic engineers and planners to follow that has been both researched and approved. The guidelines would create a more formal methodology than the current state of practice. Some ideas identified through this research for time-of-day phasing include a DSS and a methodology from a UDOT pilot study that is currently being conducted at 3300 South and 1200 West in West Valley, Utah. Each of these will be discussed in the following subsections.

6.4.1 A Decision Support System (DSS)

The University of Central Florida is currently conducting research that includes the implementation of variable left-turn phasing including time-of-day variables. Their 2013 research report presents the framework for a DSS for the dynamic evaluation of left-turn phasing in Central Florida. The purpose of this framework is to allow “an interactive evaluation of left-turn phasing and ultimately recommend phasing mode by time of day and Traffic Management Center (TMC) data to be fed into the DSS so that intersections requiring attention/modification of left-turn mode can be flagged” (Radwan et al., 2013). This research has already gone through a second phase which was published in 2016 (Radwan et al., 2016). The purpose of this second

phase was to demonstrate the ability to execute the automation of the process. The algorithm developed by this group of researchers was implemented with the goal of safely optimizing traffic operations with constant analysis in real time to determine whether it would be optimal to switch the red arrow to a FYA. The algorithm determines the time interval between the successive arrivals of vehicles and computes the corresponding headway for each lane by cycle on a second-by-second basis (Radwan et al., 2016).

In personal communication with Dr. Hatem Abou-Senna it was learned that this second phase consisted of offline field tests. His research team is currently working on Phase III of this project. After Phase III has been completed FDOT will implement their DSS online. Phase III is tentatively scheduled to be completed by the end of 2018. It is recommended that UDOT investigate the DSS more in depth once the research has been completed. The research could potentially include an investigation into the feasibility and benefit analysis of implementing such a system. A DSS could potentially be a very valuable asset that could be implemented throughout the State of Utah possibly utilizing the various intersection automated traffic signal performance measures (ATSPM) that are already in use by UDOT.

6.4.2 UDOT Pilot Study at 3300 South and 1200 West in West Valley City, Utah

During a TAC meeting on May 2, 2017, Mark Taylor of UDOT mentioned that UDOT would begin a pilot study at the intersection at 3300 South and 1200 West in West Valley City, Utah to test the effects of time-of-day signal phasing using a FYA installation. The pilot study would be designed to use the stop-bar detection of the Wavetronix Matrix sensor to detect the headway and gaps between traveling vehicles. After the gap between vehicles had been determined the system would track the changes in vehicle gap time. After critical values had been attained the signal system would change from permitted/protected left turn to protected-only left turn.

On May 23, 2017, the research team was informed that this new FYA logic was installed at the intersection located at 3300 South 1200 West in West Valley City, Utah. According to the information that was given to our research team the FYA logic includes:

- 1) Before 2:00 pm on weekdays (and all day on weekends and holidays), both directions will display a FYA (unless otherwise programmed to be protected-only).
- 2) Between 2:00 and 4:00 pm on weekdays, the logic looks for gaps in opposing through traffic. Initially an acceptable gap period of at least 6 seconds is defined. If three cycles in a row occur without at least one acceptable gap in the opposing through traffic, the left turn will begin to display protected-only indications. This is done separately for both directions. Note that even if subsequent cycles have sufficient gaps, the protected-only display remains until at least 6:30 pm (it cannot go back to FYA).
- 3) Between 4:00 and 6:30 pm on weekdays, both directions will display a protected-only indication, regardless of opposing gaps.
- 4) Between 6:30 and 7:30 pm on weekdays, the logic again looks for gaps in opposing through traffic. Once three cycles in a row have occurred where each cycle had at least one acceptable gap, the display reverts to FYA. This is done separately for both directions. Note that even if subsequent cycles do not have sufficient gaps, the FYA display remains active until the next day (it cannot go back to protected-only). It should be noted that UDOT had to increase the split (green time) to 15 seconds for the westbound left-turn to accommodate all of the demand during the protected phase.

According to this same correspondence with UDOT the time-of-day change points and duration of an acceptable gap are somewhat arbitrary. UDOT will monitor the operation of the intersection and make some fine-tuning adjustments to improve the operations and safety of the intersection. According to initial reports the logic handles the detector assignments and backup protection as well.

The pilot study could be of great use in the state of Utah if this methodology and technology was implemented and used throughout the state. It is recommended that the project be monitored closely during the pilot study to evaluate both safety and operations at the study location. If the initial results prove positive, this same system could be installed and analyzed at additional locations to verify that this procedure works from an operational perspective as well as a safety perspective at more than one intersection. After having installed and implemented this

technology a before and after analysis of both operational and safety variables should be conducted along with other ongoing research to make more informed decisions in the future.

6.5 A Record of Decision Making

In one of the regular TAC meetings Carrie Jacobson suggested that UDOT find a way to prepare summaries of why certain safety or operations decisions regarding an intersection phasing are made and making that information available for future decision makers so that it is not lost when changes are made to a signal. It was also suggested that crash details could be improved to show more detail on time of day and direction. During that same meeting Scott Jones agreed that sometimes information is lacking when a change is made due to safety and operations. Decisions are often made but the information about why the decisions were made is lost. It would be beneficial to UDOT if all of the data were more readily available.

The recommendation of the research team is that a framework similar to UDOT's ATSPM page be created. The ATSPM page currently allows users to look up traffic signal performance measures throughout each of its four regions. Some of those metrics include Purdue Phase Termination, Split Monitor, and Purdue Split Failure. In addition to those three metrics UDOT currently measures pedestrian delay, preemption details, turning movement counts, approach volume, approach delay, arrivals on red, approach speed, and yellow and red actuations. The website could contain a very similar style and format to what exists on the UDOT ATSPM page where the user can select the location where they wish to get information. After having selected a location the user would be able to choose what information they would like to receive. Currently in the ATSPM page users can choose from one of the metrics such as Purdue Phase Termination, Split Monitor, and Purdue Split Failure. In this new webpage, the user could choose information about what type of signal phasing and timing is in use at a particular intersection or corridor, when changes to the signal timing or phasing were made, and crash data.

6.6 Chapter Summary

Several limited recommendations have been noted in this chapter based on the synthesis of practice and agency surveys that have been conducted. Because the objective of this research was not to implement the recommendations made, each of these would need to be researched more thoroughly in the future before any implementations should be made. Each topic mentioned previously including analysis of decision boundaries for left-turn treatments, evaluation of left-turn volume criteria, time-of-day and FYA warrants, and a record of decision making all have the potential to improve the current left-turn phasing practices in the state. Each of these topics could improve not only the left-turn warrant practices currently used, but can also improve the operational and safety aspects of the roadways in Utah.

7.0 Conclusions

This chapter contains a summary of what was completed in this research. It contains the research objectives, the project tasks, as well as a summary of the limited recommendations presented in previous chapters.

7.1 Research Objectives

The primary objective of this research was to produce a synthesis of left-turn signal warranting procedures and guidelines across the nation and to compare the information gathered through the synthesis produced by this research with UDOT warranting procedures and guidelines to make limited recommendations on possible ways to improve the process. These objectives were accomplished by:

- 1) Reviewing the current UDOT warranting procedures and guidelines documentation, including any recent updates to the procedures.
- 2) Reviewing the research conducted by the University of Utah on *Safety Effects of Protected and Protected/Permitted Left-Turn Phases*, that included a review of the state DOT survey conducted as part of the research, identify what additional information would be needed to meet the objectives of the study, and requesting information accordingly.
- 3) Coordinating with other organizations including cities, counties, and research organizations to supplement the state DOT data gathered during the synthesis preparation task.
- 4) Comparing the information gathered in the synthesis with current left-turn warranting procedures and guidelines in Utah and making limited recommendations on ways to improve the current warranting procedures and guidelines.

7.2 Project Tasks Completed

This section contains a brief summary of all of the tasks completed as part of this research. Sections that will be discussed include: the UDOT warranting procedure and guidelines review, the University of Utah research review, the synthesis of practice and literature review, and the recommendations section which includes the final report to UDOT.

7.2.1 UDOT Warranting Procedure and Guidelines Review

UDOT left-turn warranting procedures and guidelines were closely examined. This included discussion with those who have been involved with the development and recent updates of the guidelines, as well as the identification of missing guidelines from the current procedure including FYA warrants and guidelines, time-of-day restrictions (specifically for FYA), changing between protected left-turn and permitted phasing, and guidelines related to dual left turns.

7.2.2 Review of the Research Conducted by the University of Utah

The University of Utah was completing a research study focused on identifying the safety effects of protected left-turn and protected/permissive left-turn phases at the time of this research. As part of University of Utah research, surveys were conducted to collect information on the state of practice for left-turn phasing from all 50 state DOTs. The outreach effort resulted in 44 responses from state DOTs regarding the type of criteria used to inform decisions on left-turn phasing. The survey results from this effort were reviewed as part of this task. Based on the results of the effort, additional questions were identified for the state DOT representatives. This task also involved coordination with the University of Utah research team to glean from them additional information that may not be easily obtained from the survey results. This was critical in order to avoid duplication of efforts and to be sensitive of the time required for state DOT representatives to respond to the survey.

7.2.3 Synthesis of Practice/Literature Review

Using the data collected from the UDOT warranting procedures and guidelines review, as well as the University of Utah research, the purpose of this task was to review the data collected

and to identify missing information that can be obtained through additional surveys of state DOT representatives as well as representatives from other organizations. The research team worked closely with Mark Taylor at UDOT to focus in on key players in this area and to submit a survey to these organizations. In addition, a member of the research team attended the Transportation Research Board (TRB) Annual Meeting in January 2017 to collect data related to the topic.

7.2.4 Recommendations and Conclusions/Final Report and Presentation

In this task, the research team identified limited recommendations and conclusions for UDOT based upon observations and analyses in each of the tasks above. The compilation of this project report documents the results of the research tasks.

7.3 Summary of Limited Recommendations

Based on the synthesis of practice conducted, it is recommended that the following topics be researched further:

- Analysis of decision boundaries for left-turn treatments.
- Comparisons of the current volume criteria.
- Time-of-day and FYA warrants.
- Implementing a record of decision making.

Each of these topics has the potential to improve not only the left-turn warrant practices currently used, but has the potential to improve the operational and safety aspects of the roadways in Utah. Some of the topics have been funded at least in part by UDOT during the 2017 UTRAC Workshop. Topics including the analysis of decision boundaries for left-turn treatments and the UDOT Pilot Study at 3300 South and 1200 West in West Valley City, Utah have already been approved or funded and have been begun in some capacity or another.

The purpose of the analysis of decision boundaries for left-turn treatments research is to evaluate the mixture of left-turn and opposing through traffic volumes for permitted vs. protected left-turn phasing at intersections. Additionally, new volume thresholds could be identified as a

result of the data. These new threshold values would help to identify when to switch from permissive to protected phasing at intersections, as well as when to transition from single to dual left-turn lanes.

One of the limited recommendations that the research team has put forth includes the consideration of comparing and then potentially optimizing the left-turn volume warrants. As previously mentioned there are three different parts to these recommendations for future research projects. The first involves researching the effects of changing or restructuring the volume cross product thresholds. The research would include analyzing the safety and operational effects of creating separate volume cross product threshold values for two and three opposing lanes. The second recommendation includes researching the operational and safety effects of changing the volume cross product thresholds by increasing, decreasing, or maintaining the current volume threshold values. The third involves researching the possibility of including right turn and pedestrian volumes in the left-turn warrants. The last recommendation for future research, regarding left-turn volumes, is to conduct a state by state comparison of left-turn volume cutoff values. A synthesis similar to this report can be conducted in order to compare and contrast the practices of the state of Utah with other states throughout the country.

The recommendations given would need to be analyzed to verify that there are significant safety and operational effects that are caused by these changes. Changes made may potentially yield positive or negative operational and safety results. Conversely, it is possible that changes to the volume cross products may not yield significant effects and the changes to the thresholds would not change in terms of operations and safety. As such, these recommendations for future research would have to be investigated further in order to analyze both the safety and operational impacts of changing the volume warrants.

The recommendations regarding FYA and time-of-day warrants include two different research topics. If UDOT is interested in having FYA operations throughout the majority of the day, it is recommended that research be conducted on the feasibility of implementing a DSS. The University of Central Florida is conducting research that deals with the implementation of variable left-turn modes including time-of-day variables. Their 2013 research paper presents the framework for a DSS for the dynamic evaluation of left-turn phasing in Central Florida. The

purpose of this framework is to allow “an interactive evaluation of left-turn phasing and ultimately recommend phasing mode by time of day and TMC data to be fed into the DSS so that intersections requiring attention/modification of left-turn mode can be flagged” (Radwan et al., 2013). This research has already gone through a second phase which was published in 2016. Phase III is tentatively scheduled to be completed by the end of 2018. The second recommendation includes monitoring and evaluation of the pilot study now being conducted at 3300 South and 1200 West in West Valley City, Utah. It is recommended that the intersection be monitored closely during the pilot study to evaluate both safety and operations at the study location. If the initial results prove positive, this same system could be installed and analyzed at additional intersections to verify that this procedure works from an operational perspective as well as a safety perspective at more than one intersection. After having installed and implemented this technology a before and after analysis of both operational and safety variables should be conducted along with other ongoing research to make more informed decisions in the future.

It is also recommended that a record of decision making be considered for the state of Utah. This would include a framework similar to the UDOT ATSPM page. The website could contain a very similar style and format to what exists on the UDOT ATSPM page where the user can select the location where they wish to get information. After having selected a location the user would be able to choose what information they would like to receive. Currently in the ATSPM page users can choose from one of the metrics such as Purdue Phase Termination, Split Monitor, and Purdue Split Failure. In this new webpage, the user could choose information about what type of signal phasing and timing is in use at a particular intersection or corridor, when and why changes to the signal timing or phasing were made, and crash data for the intersection. Each topic and part of the limited recommendations can be beneficial to UDOT and can be used to reach UDOT goals of increasing safety and operations throughout the state of Utah.

REFERENCES

- Abou-Senna, H. (2017). Center for Advanced Transportation Systems Simulation (CATSS), University of Central Florida, Orlando, FL. Personal Communication.
- American Association of State and Highway Transportation Officials (AASHTO). (2010). Highway Safety Manual. Washington, DC.
- Brehmer, C. L., Kacir, K. C., Noyce, D. A., Manser, M. P. (2003). NCHRP Report 493: Evaluation of Traffic Signal Displays for Protected/Permissive Left Turn Control. Transportation Research Board, Washington, DC.
- Chalise, S., Radwan, E., and Abou-Senna, H. (2017). "Analysis of Variable Left Turn Mode by Time of Day for Flashing Yellow Arrow Signals Using the Left Turn Delay Prediction Models." TRB Annual Meeting Online 2017 & Archived Meeting Content, Transportation Research Board, <<http://amonline.trb.org/63532-trb-1.3393340/t024-1.3404251/732-1.3404477/17-06225-1.3400907/17-06225-1.3404486>> (Feb. 8, 2017).
- Chen, L., Chen, C., and Ewing, R. (2015). "Left-Turn Phase: Permissive, Protected, or Both? A Quasi-Experimental Design in New York City." *Accident Analysis & Prevention*, vol. 76, pp. 102-109.
- DePauw, E. Daniels, S., Brijs, T., Hermans, E., and Wets, G. (2013). "The Traffic Safety Effect of Protected Left-Turn Phasing at Signalized Intersections". Proceedings of the 26th International Co-operation on Theories and Concepts in Traffic Safety (ICTCT) Workshop. Slovenia.
- Federal Highway Administration (FHWA). (2008). Traffic Signal Timing Manual-Traffic Signal Design. <<https://ops.fhwa.dot.gov/publications/fhwahop08024/chapter4.htm>> (Jun. 14, 2017).
- Federal Highway Administration (FHWA). (2013). Signalized Intersections Informational Guide. <<http://safety.fhwa.dot.gov/intersection/conventional/signalized/fhwas13027/fhwas13027.pdf>> (Feb. 2, 2017).

- Hajbabaie, A. (2017). A Data Driven Safety Assessment of Various Left-Turn Phasing Strategies. Department of Civil and Environmental Engineering, Washington State University. Project Proposal
- Hales Engineering. (2016). "Left-turn Phasing Criteria Update," [Memorandum].
- Harkey, D. L., Srinivasan, R., Baek, J., Council, F. M., Eccles, K., Lefler, N., Gross, F., Persaud, B., Lyon, C., Hauer, E., and Bonneson, J. A. (2008). NCHRP Report 617: Accident modification factors for traffic engineering and ITS improvements. Transportation Research Board, Washington, DC.
- Indiana Department of Transportation (INDOT). (2015). "Left-Turn Signal Display," [Operations Memorandum 15-04 Signals]. Personal Communication.
- McCarroll, J. (2009). Flashing Yellow Arrows in Oregon. Presentation available online from http://scote.transportation.org/Documents/05_JoelMcCarrollFlashingYellowArrowsinOregonwithvideo.ppt.
- Noyce, D. A., Bergh, C. R., and Chapman, J. R. (2007). NCHRP Web-Only Document 123: Evaluation of the Flashing Yellow Arrow Permissive-Only Left-Turn Indication Field Implementation. Transportation Research Board, Washington, DC.
- Perez, R. A. (2010). "Safety Implications of Conversions to Flashing Yellow Arrow Indications." City of Federal Way. http://www.westernite.org/Sections/washington/newsletters/Safety_Redux_2009_Rick_Perez (Mar. 6, 2017).
- Pulugurtha, S. S., and Chittoor Khader, K. S. (2014). "Assessing the Effect of Introducing a Permitted Phase Through the Use of Flashing Yellow Arrow Signal for Left-Turning Vehicles." *International journal of injury control and safety promotion*. 21.4: 338-347.
- Radwan, E., Abou-Senna, H., Navarro, A., and Chalise, S. (2013) "Dynamic Flashing Yellow Arrow (FYA) A Study on Variable Left Turn Mode Operational and Safety Impacts." FDOT Contract BDK78 977-15, Center for Advanced Transportation Systems Simulation (CATSS), University of Central Florida, Orlando, FL.

- Radwan, E., Abou-Senna, H., Eldeeb, H., and Navarro, A. (2016) "Dynamic Flashing Yellow Arrow (FYA) A Study on Variable Left-Turn Mode Operational and Safety Impacts Phase II – Model Expansion and Testing." FDOT Contract BDV24-977-10, Center for Advanced Transportation Systems Simulation (CATSS), University of Central Florida, Orlando, FL.
- Raessler, A., and Yang, J. (2017). "Derivation of Decision Boundaries for Left Turn Treatments at Signalized Intersections." TRB Annual Meeting Online 2017 & Archived Meeting Content, Transportation Research Board, <<http://amonline.trb.org/63532-trb-1.3393340/t024-1.3404251/648-1.3404633/17-02491-1.3399674/17-02491-1.3404676>> (Feb. 8, 2017).
- Rodegerdts, L. A., Nevers, B., and Robinson, B. (2004). Signalized Intersections: Informational Guide, FHWA-HRT-04-091. Federal Highway Administration, U.S. Department of Transportation, Washington, DC.
- Saito, M., Frustaci, J. B., and Schultz, G. G. (2016). "Life-Cycle Benefit-Cost Analysis of Safety Related Improvements on Roadways," Report UT-16.15, Utah Department of Transportation Traffic & Safety, Research Divisions, Salt Lake City, UT.
- Schattler, K. L., Anderson, E., and Hanson, T. (2016). Safety Evaluation of Flashing Yellow Arrows for Protected/Permissive Left-Turn Control. Illinois Center for Transportation/Illinois Department of Transportation. <https://apps.ict.illinois.edu/projects/getfile.asp?id=4814>
- Schultz, G. G., Dowell, A., Roundy, R., Saito, M., and Reese, C. (2014). "Evaluating the Safety Effects of Signal Improvements." *Transportation Research Record: Journal of the Transportation Research Board*. No. 2435: 19-26.
- Scurry, K. (2014). "Introduction to Crash Modification Factors," Report FHWA-SA-13-015, U.S. Department of Transportation Federal Highway Administration, Washington, DC. <<https://safety.fhwa.dot.gov/tools/crf/resources/cmfs/docs/intro.pdf>> (Feb. 18, 2017).
- Searle, J. (2017). Hales Engineering. Personal Communication.

- Shea, M. S., Medina, J. C., and Porter, R. J. (2016). "Safety Effects of Protected and Protected/Permitted Left-Turn Phases: Literature Review and Current State of Practice," University of Utah Traffic Lab, Salt Lake City, UT.
- Simpson, C.L., and Troy, S.A. (2015). "Safety Effectiveness of Flashing Yellow Arrow: Evaluation of 222 Signalized Intersections in North Carolina." *Transportation Research Record: Journal of the Transportation Research Board*. No. 2492: 46-56.
- Srinivasan, R., Lyon, C., Persaud, B., Baek, J., Gross, F., and Smith, S. (2012) "Crash Modification Factors for Changes to Left-Turn Phasing". *Transportation Research Record: Journal of the Transportation Research Board*, No. 2279. pp. 108-117.
- Transportation Research Board (TRB). (2000). Highway Capacity Manual, 3rd Ed. Washington, DC.
- Transportation Research Board (TRB). (2010). Highway Capacity Manual, 3rd Ed. Washington, DC.
- Utah Department of Transportation (UDOT). (2014). Left-Turn Phases at Signalized Intersections, <<https://www.udot.utah.gov/main/uconowner.gf?n=22168023889671869>> (Feb. 2, 2017).
- Yi, Q. (2012). Use of Flashing Yellow Operations to Improve Safety at Signals with Protected Permissive Left Turn (PPLT) Operations: Texas Southern University. <https://library.ctr.utexas.edu/hostedpdfs/txdot/psr/6568.pdf>
- Yu, L., Chen, X., Yu, L., Wang, Y., Zhang, M., Yuan, P., Persad, K.R. (2009). "Development of left-turn operations guidelines at signalized intersections". Report No. FHWA/TX-09/0-5840-1. Department of Transportation Studies, Texas Southern University. Research and Technology Implementation Office, Texas Department of Transportation. https://nacto.org/docs/usdg/development_left_turn_operations_guidelines_yu.pdf

APPENDIX A: UDOT 2014 LEFT-TURN PHASING GUIDELINES

Updated November 13, 2014

Purpose

To define the process for warranting left-turn phasing at existing signalized intersections.

UDOT Recommended Guidelines

Guidelines for Left-Turn Phasing

The following flow-chart has been established as criteria for recommending left-turn phasing at signalized intersections. A left-turn phase may be installed after less restrictive measures to reduce delay, congestion, and crashes have been considered. The overall signalized corridor/network operations should be considered when evaluating the impacts of left-turn phasing. Even if the criteria in the flowchart are met for left-turn phasing, engineering judgment should be used to determine whether left-turn phasing is implemented.

Before completing the flowchart for left-turn phasing, the intersection should be evaluated by the TOC to determine if signal timing adjustments can mitigate the problem. The intersection should also be evaluated for sight distance and geometric issues that may determine whether a protected-only left-turn phase is required. A field review is recommended for all sites before changes to left-turn phasing are implemented. Criteria for left-turn phasing are found on the attached flowchart.

Guidelines for Dual Left-Turn Lanes

UDOT recommends the following guidelines in helping to make decisions when to install dual left-turn lanes.

- I. A capacity sensitivity analysis should be performed. When performing the capacity sensitivity analysis, the default analysis values in Synchro should be:
 - a. Cycle length: 120 seconds
 - b. Ideal saturation flow rate: 1900 vphpl
 - c. Percent heavy vehicles: 2%
 - d. Lane widths: 12 feet
 - e. Analyze with no parking and non CBD
 - f. Optimize splits

Table 1 below shows the recommended left turn volumes and the opposing through volume to capacity (v/c) ratio to use in assisting to make the decision for dual left-turns. The v/c ratio is calculated using HCM 2010 methodologies.

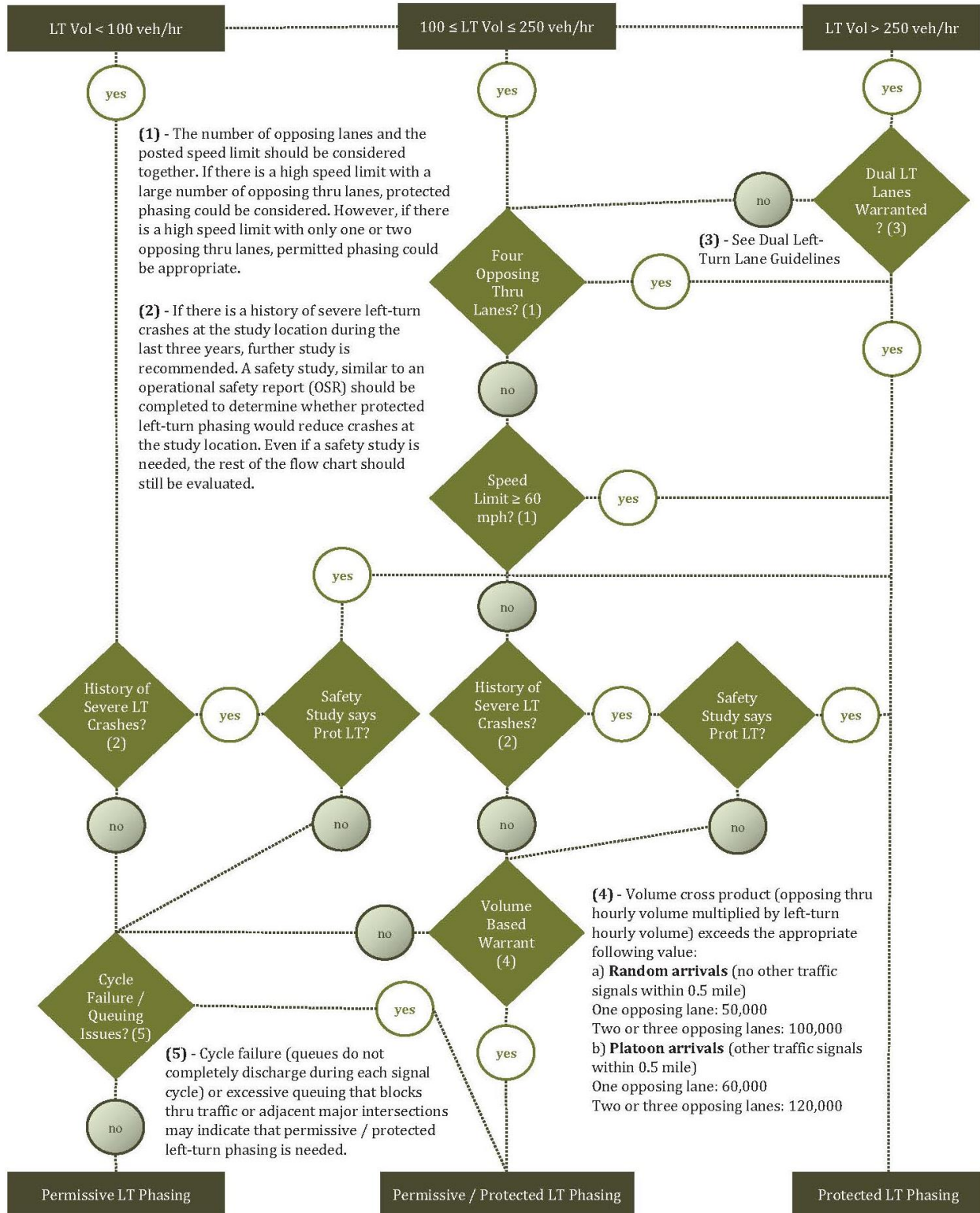
Table 1: Capacity Analysis Guidelines

Left-Turn Volume	Opposing Through V/C \geq	Recommend
250 - 269	0.95	Dual Left-Turn Lanes
270 - 279	0.75	Dual Left-Turn Lanes
280 - 319	0.65	Dual Left-Turn Lanes
320 - 359	0.6	Dual Left-Turn Lanes
360 - 389	0.55	Dual Left-Turn Lanes
390 - 420	0.5	Dual Left-Turn Lanes
≥ 420		Dual Left-Turn Lanes

- II. The number of hours where left-turn volume meets the guidelines in the capacity analysis in Table 1 should be considered where the dual left-turn lanes provide a benefit. A comparison with the vehicle delays should be made during the other non-peak hours in the day.
- III. The location of the intersection where the dual left is being considered should also consider the lane distribution that will be obtained. For example, if the intersection is close to a freeway on-ramp, there may not be good lane utilization since vehicles will favor the lane providing the best access to the ramp.
- IV. Consideration should be given for the need to minimize the green time given to left turns on one approach so that added green time is available for the other phases.
- V. Compatibility of the dual left exclusive phasing operations with the signal coordination should be evaluated.
- VI. The Designer and Project Manager shall consult with the Region Traffic Operations Engineer and the Division of Traffic & Safety before adding dual left-turn lanes when the left-turn volume is less than 420 vph.
- VII. If there is no opposing through movement, such as at a three-way "T" intersection, then no additional signal phase is needed. Instead of using the above volume and v/c criteria, consideration should be given to opposing pedestrian phases, available right-of-way needed for the additional lane, and existing left-turn queue lengths at the intersection. If cycle failure (queue doesn't clear during each signal cycle) is occurring often, dual left-turn lanes should be considered.

Left-Turn Phasing Guidelines

Updated November 13, 2014



APPENDIX B: LEFT-TURN PHASING CRITERIA UPDATE MEMORANDUM

MEMORANDUM

Date: July 20, 2016
To: Jesse Sweeten, P.E.
Traffic and Safety Design Engineer
From: Hales Engineering
Subject: Left-turn Phasing Criteria Update

UT13-476

Purpose

There have been recent discussions regarding the guidelines currently used by UDOT Traffic and Safety to determine when left-turn phasing at signalized intersections is appropriate, specifically regarding the volume based warrant. The volume based warrant is based on the volume cross product, which is defined as the left-turn volume multiplied by the opposing through volume. Currently, opposing right-turning vehicles are excluded from the volumes on an approach when calculating the volume cross product for a left-turn movement. Observations by engineers in the field during data collection indicate that right-turning vehicles may conflict with the opposing left-turn movement as much as vehicles in the through lanes. Pedestrians can also conflict with the left-turn movement.

Concern has also been raised with regards to the volume cross product thresholds being too low, resulting in left-turn phasing being implemented too often, or at intersections where it is not truly needed.

The purpose of this memorandum is to compare the volume cross product threshold values with values recommended by other agencies, and summarize an analysis completed by Hales Engineering to determine how to best include right-turning vehicles in the volume cross product calculations.

Comparison of UDOT Left-Turn Phasing Criteria

As mentioned previously, there have been concerns that the current UDOT Left-Turn Phasing Guidelines are too "liberal," and that left-turn phasing is being installed too often. A comparison was completed between the old UDOT Left-Turn Phasing criteria, and the new criteria, which was adopted November 13, 2014. Figure 1 compares the left-turn studies that were completed in 2013 & 2014 under the old criteria, and the

studies completed in 2015 & 2016 under the new criteria. As shown in Figure 1, using the old UDOT criteria, approximately 48 percent of the intersections studied found that left-turn phasing was warranted. Using the new criteria, approximately 53 percent of the intersections studied found that left-turn phasing was warranted. These percentages are fairly close and show that there have not been a significant increase in the percent of intersections that are warranting left-turn phasing. It may also indicate that as more studies are completed, the requestors are becoming more familiar with what intersection volumes / characteristics may need left-turn phasing.

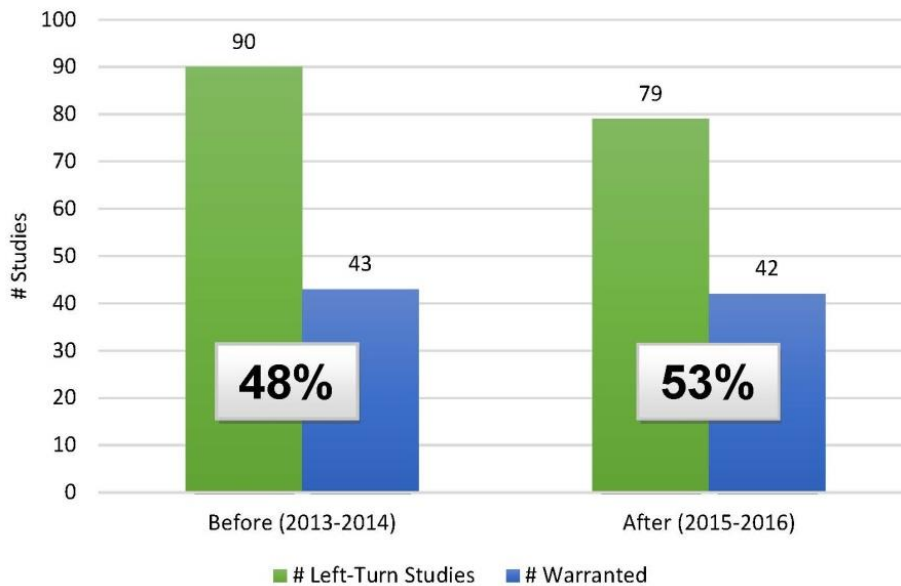


Figure 1: Comparison of UDOT Left-Turn Phasing Criteria

Existing UDOT Criteria

There are three main parts contained in the flowchart for the Left-Turn Phasing Guidelines. These include: 1) History of Severe Left-turn Crashes, 2) Volume Based Warrant and 3) Cycle Failure / Queuing Issues. This memorandum discusses the Volume Based Warrant. The volume cross product thresholds in the current Left-Turn Phasing Guidelines (updated November 13, 2014) are shown in Table 1. There are different thresholds based on the number of opposing through lanes, as well as for the proximity of upstream traffic signals. Opposing right-turning vehicles are generally not included in volume cross-product calculations.

Table 1 Current UDOT Volume Cross Product Thresholds

UDOT Left-Turn Phasing Criteria		
Number of Opposing Lanes	Volume Cross Product	
	Random Arrivals	Platoon Arrivals
1	50,000	60,000
2 or 3	100,000	120,000
Adopted November 13, 2014		

Criteria Used by Other Organizations

As shown in Table 2, the Highway Capacity Manual (HCM) (TRB 2010) recommends that left-turn phasing be implemented when the minimum cross-product thresholds of 50,000, 90,000, and 100,000 are met for one, two, and three opposing through lanes respectively. (No differentiation is given for arrival type.) The HCM also recommends that right-turning vehicles be included in the cross-product calculation. Right-turning vehicles can be excluded if it is determined that left-turning drivers can safely ignore the opposing right-turning vehicles.

Table 2 Highway Capacity Manual Volume Cross Product Thresholds

HCM Left-Turn Phasing Criteria	
Number of Opposing Lanes	Volume Cross Product
1	50,000
2	90,000
3	100,000
HCM 2010	

As shown in Table 3, the Federal Highway Administration (FHWA) recommends left-turn phasing when the volume cross-product meets the minimum threshold of 45,000 for one opposing lane or 90,000 for two opposing lanes for random arrivals, or 50,000 or 100,000 for platoon arrivals. The FHWA recommends that left-turn phasing be implemented when the left-turn movement crosses three or more lanes of opposing through traffic, regardless of the volume cross-product.

Table 3 Federal Highway Administration Volume Cross Product Thresholds

FHWA Left-Turn Phasing Criteria		
Number of Opposing Lanes	Volume Cross Product	
	Random Arrivals	Platoon Arrivals
1	45,000	50,000
2	90,000	100,000
3	Install Left-Turn Phasing	
FHWA-HRT-04-091		

When compared to the standards set forth in the HCM and by the FHWA, the volume criteria used by UDOT for the recommendation of left-turn phasing at signalized intersections is notably higher. It can be concluded that left-turn phasing is recommended less frequently than if the HCM or FHWA thresholds were used.

Analysis

Hales Engineering compiled peak hour turning movement count data from 32 of the most recent left-turn studies completed by UDOT Traffic and Safety throughout the state. The proportion of right-turning vehicles to through vehicles was calculated based on the number of through lanes on each approach. As shown in Table 4, on intersection approaches with one through lane, right-turning vehicles accounted for approximately 42% of all non-left-turning traffic on the approach. Right-turning vehicles made up approximately 11% of traffic on approaches with two through lanes, and approximately 14% on approaches with three through lanes.

Table 4 Proportion of Right-Turning Vehicles to Through Vehicles

Proportion of Right-Turning Vehicles to Thru Vehicles	
Number of Thru Lanes	% of Right Turns
1	42%
2	11%
3	14%
Hales Engineering, 2016	

One alternative for including opposing right-turn vehicles in the volume cross-product calculations would be to increase the volume cross product thresholds proportionally. With the addition of right-turning vehicles to the calculations, the volume cross-product

thresholds could be increased by 40% for approaches with one through lane, and by 12% for approaches with two or three through lanes. The possible volume cross product thresholds are shown in Table 5, assuming a proportionally increase.

Table 5 Possible Volume Cross Product Thresholds

Possible Increase to UDOT Left-Turn Phasing Thresholds			
Number of Opposing Lanes	Volume Cross Product		
	Random Arrivals	Platoon Arrivals	% Increase
1	70,000	84,000	40%
2 or 3	112,000	135,000	12%

Next Steps

There are several alternatives that could be used to address the questions regarding the left-turn phasing guidelines. Some of these alternatives include:

1. Keep the criteria the same – rely on cycle failure / queuing for specific intersection concerns.
2. Update criteria to state that the cross product is calculated using both the opposing through movement and the right-turn movements.
3. Add a footnote to existing criteria stating that right-turns can be included based on engineering judgement.
4. Increase the cross product thresholds without including right-turns.
5. Increase the cross product criteria proportionally to the right-turns as shown in Table 5.
6. Add an additional set of criteria for instances where right-turns should be counted.

Each of these alternatives would have a different impact on the percentage of intersections that warrant left-turn phasing. Alternative 1 would keep the percentage as it is currently. Alternatives 2 and 3 would increase the percentage of intersections studied that warrant left-turn phasing. Alternative 4 would decrease the percentage of intersections studied that warrant left-turn phasing. Alternative 5 would keep the percentage approximately equal. Alternative 6 would change the percentage based on the new criteria (not yet specified).

APPENDIX C: SURVEY QUESTIONS

FYA Survey

Questions submitted to state traffic or signal engineers:

- 1) Please enter your name below
- 2) Please enter your email below
- 3) Please enter your phone number below
- 4) Please enter your organization below (ex. Utah Department of Transportation, City of Provo, etc.)
- 5) Does your state utilize Flashing Yellow Arrow (FYA) installations?
- 6) Does your state have specific warrants/guidelines pertaining to FYA installations?
- 7) What are those warrants/guidelines? Feel free to copy a link into the text box below that explains the warrants/guidelines.
- 8) Does your state utilize time-of-day signal phasing? (e.g., does the intersection's signal phase change from Protected-Only left-turn (PLT) or Protected-Permissive left turn (PPLT) to Flashing Yellow Arrow (FYA) or any other form of similar change based on time of day).
- 9) Does your state have specific warrants/guidelines for time-of-day signal phasing?
- 10) What are those warrants/guidelines? Feel free to copy a link into the text box below that explains the warrants/guidelines.
- 11) Are specific formulas or algorithms used in time-of-day signal phasing?
- 12) What are those formulas/algorithms? Please feel free to copy a link into the text box that explains the formulas/algorithms.

- 13) What is your state's policy on changing signal phasing? How/when are you implementing changes from other traffic signal phasing such as Protected-Only left turn (PLT), Protected-Permissive left turn (PPLT), or Permissive Left Turn to FYA?

Left-Turn Signal Warrant Study + FYA Survey

Questions submitted to state, city, and county traffic or signal engineers:

- 1) Please enter your name below
- 2) Please enter your email below
- 3) Please enter your phone number below
- 4) Please enter your organization below (ex. Utah Department of Transportation, City of Provo, etc.)
- 5) Does your jurisdiction utilize left-turn signal phasing guidelines?
- 6) If the left-turn phasing guidelines are in document form please provide a link to the document. If a link is not available please send it as an attachment to signalwarrantstudy@gmail.com. If that is not possible please type N/A.
- 7) What safety/crash criteria do you consider for left-turn signal phasing?
- 8) What volume criteria do you consider for left-turning signal phasing? Do you utilize a cross product or a combination of left-turn volume and opposing through volumes? Do you use a different volume criteria for permissive/protected or protected only phasing?
- 9) What are the progression steps in left-turn phasing? Do you progress from permissive, to permissive/protected, to protected only? Or some other progression sequence?
- 10) Does your jurisdiction consider delay as part of left-turn signal phasing? (Ex. the FHWA considers delay in their 2008 flowchart. Vehicle delay considers both individual left-turn vehicle delay and the total left-turn vehicle-hours of delay during the peak hour. A 35

sec/veh delay or a 2.0 veh-hr delay will warrant protected/permissive left turn (desired) or protected left-turn-only phasing.)

- 11) What are those delay criteria? (Ex. the FHWA considers delay in their 2008 flowchart. Vehicle delay considers both individual left-turn vehicle delay and the total left-turn vehicle-hours of delay during the peak hour. A 35 sec/veh delay or a 2.0 veh-hr delay will warrant protected/permissive left turn (desired) or protected left-turn-only phasing.)
- 12) Does your jurisdiction allow permissive dual left turns?
- 13) How many dual left-turn locations are you aware of in your jurisdiction?
- 14) Does your state utilize Flashing Yellow Arrow (FYA) installations?
- 15) Does your state have specific warrants/guidelines pertaining to FYA installations?
- 16) What are those warrants/guidelines? Feel free to copy a link into the text box below that explains the warrants/guidelines.
- 17) Does your state utilize time-of-day signal phasing? (e.g., does the intersection's signal phase change from Protected-Only left turn (PLT) or Protected-Permissive left turn (PPLT) to Flashing Yellow Arrow (FYA) or any other form of similar change based on time of day).
- 18) Does your state have specific warrants/guidelines for time-of-day signal phasing?
- 19) What are those warrants/guidelines? Feel free to copy a link into the text box below that explains the warrants/guidelines.
- 20) Are specific formulas or algorithms used in time-of-day signal phasing?
- 21) What are those formulas/algorithms? Please feel free to copy a link into the text box that explains the formulas/algorithms.

22) What is your state's policy on changing signal phasing? How/when are you implementing changes from other traffic signal phasing such as Protected-Only left turn (PLT), Protected-Permissive left turn (PPLT), or Permissive Left Turn to FYA?

APPENDIX D: INDOT LEFT-TURN SIGNAL DISPLAY WORKSHEET

Left-Turn Signal Display Worksheet

Intersection:

Analysis Date:

Approach:

Analyst:

Factors	Parameter	Peak Hour Value	Risk Level	Avg. Daytime Value	Risk Level	Avg. Nighttime Value	Risk Level
Sight Distance	Sight Distance (e.g. horizontal or vertical curve or intersection skew) ≥ 5.5 sec of travel time = Low < 5.5 sec of travel time = Elevated [example: for 50 mph, 5.5 sec ≈ 400 ft]						
	Left-Turn Offset* ≥ 0 ft = Low 0 < x ≤ -6 ft = Normal < -6 ft = Elevated <small>*See FHWA Publication: FHWA-HRT-09-036</small>						
	Opposing Left-Turn Use** < 30 vph = Low 30 ≤ x < 60 vph = Normal ≥ 60 vph = Elevated <small>**Not Applicable if Left-Turn Offset > 0</small>						
Traffic Volume	Opposing Thru Volume < 400 vph = Low 400 ≤ x < 800 vph = Normal ≥ 800 vph = Elevated						
	Left-Turn Volume ≤ 60 vph = Low 60 < x ≤ 120 vph = Normal > 120 vph = Elevated						
Number of Lanes	Opposing Thru Lanes 1 = Low 2 = Normal ≥ 3 = Elevated						
	Left-Turn Lanes 1 = Low ≥ 2 = Elevated						
Other	Opposing Speed Limit < 45 = Low 45 ≤ x ≤ 50 = Normal > 50 = Elevated						
	Left Turn Crashes (12 month period) < 4 crashes = Low 4 ≤ x < 6 crashes = Normal ≥ 6 crashes = Elevated						
		Peak Hour Value		Avg. Daytime Value		Avg. Nighttime Value	
Number of Low Risk:							
Number of Normal Risk:							
Number of Elevated Risk:							
Recommended Left-Turn Display:							